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Bench Scale Studies of Limestone Injection for SO_2 Control

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16. ABSTRACT

The report gives results of experiments in a boiler simulator furnace, indicating that the parameters of major importance to SO2 capture are thermal environment, calcium/sulfur ratio, and sorbent composition. Thermal environment (local temperature) had a strong effect on the utilization of dry sorbents injected directly into the furnace. Burner staged experiments showed the influence of temperature most clearly: a reduction in peak flame temperature, due to either cooling in the radiant zone or a reduction in load, increased sulfur capture significantly. Changes in other combustion parameters (e.g., sorbent location and injection velocity) had secondary effects on sulfur capture. The influence of sorbent type (Vicron 45-3, Vicron 15-15, Michigan marl, hydrated lime--Ca(OH)2, and dolomite) on sulfur capture was studied at five different combustion conditions: Indiana No. 3 coal fired in the distributed mixing burner with and without external cooling, Indiana No. 3 coal under externally staged conditions, and propane doped with H2S. In general, dolomite gave good capture under all conditions. Hydrated lime appeared to be most sensitive to thermal environment, and dolomite was least sensitive. High captures were observed for all sorbents when the primary fuel was propane/H2S.

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Coal		Stationary Sources	21D
Combustion		Limestone Injection	21B
Calcium Carbonates			07B
Sulfur Dioxide			
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ABSTRACT

This report describes the research efforts carried out in one task of EPA contract 68-02-2667 and addresses the use of calcium-based sorbents for in situ sulfur capture under combustion conditions which minimize nitrogen oxide formation from pulverized coal. A boiler simulator furnace (BSF) was designed and constructed, and a test matrix with three major categories was designed to meet the task objectives: (A) Combustion Parameter Screening; (B) Thermal History/Sulfur Chemistry Studies; and (C) Fuel and Sorbent Studies. The BSF was designed to simulate a variety of boiler temperature histories by heat extraction at various locations.

The results of the combustion parameter screening studies (Series A) indicated that thermal environment impacted sulfur capture significantly. Specifically, when peak flame temperatures decreased, capture increased. Changes in other parameters, such as sorbent location and injection velocity, produced secondary effects on sulfur capture.

The purpose of the Series B set of experiments was to clarify the effect of thermal environment on sulfur capture by conducting experiments to investigate sulfur evolution and speciation in the fuel-rich zone of the furnace. Tests were also run to define the influence of thermal environment on sulfur capture under both internally and externally staged conditions. The results from the Series B set of experiments can be summarized as follows: under fuel-rich conditions, sulfur species appear to be far from equilibrium; sulfur capture in the fuel-rich zone does not appear to be significant even with gaseous fuels; and with coal, capture in the rich zone is limited because of sulfur carryover in the solid phase.

In the Series C experiments, the effects of sorbent and fuel properties were investigated. For the fuel studies, propane doped with H_2S, a coal-water slurry, and a lignite coal all gave better capture than an Indiana coal. For the sorbent studies, four sorbent types were studied, one with two particle sizes. In general, dolomite was the best sorbent regardless of fuel or firing conditions. Particle size (Vicron 45-3 vs. Vicron 45-15) had little effect over the range tested and fuel type (gas vs. coal) had varying effects on capture for lime and Vicron 45-3.

Major conclusions reached from this study were that thermal history, calcium concentration and sorbent composition were of major importance in sulfur removal. In addition, fuel-rich capture does not appear to be significant. Of the sorbents tested, dolomite produced the highest captures and the hydrated lime was most sensitive to changes in thermal conditions. Of the fuels tested, Indiana coal gave lower capture than a lignite, propane with H_2S and a coal-water slurry.

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1.0 PROJECT SUMMARY

This report describes the research studies carried out in one task of EPA Contract No. 68-02-2667. The Development of Criteria for Extension of Applicability of Low Emission, High Efficiency Coal Burners. This task involved the use of a series of bench-scale facilities to determine the process parameters controlling the capture of sulfur species by calcium based sorbents when pulverized coal is burned under low NO_x conditions.

1.1 Objectives

Although coal is the most abundant source of fossil fuel energy in the United States, its use poses several serious problems for society, not the least of which is the emission of atmospheric pollutants. The combustion of coal results in the formation of sulfur and nitrogen oxides, which have been identified as precursors for acid precipitation. Although the evidence is not conclusive, it is generally recognized that the environmental damage caused by acid precipitation can be mitigated by reductions in emissions of these precursors from coal fired power plants. Consequently, there is a need to develop efficient and cost effective control techniques for these pollutants. This report addresses the use of calcium based sorbents for in-situ sulfur capture under combustion conditions which minimize nitrogen oxide formation from pulverized coal combustion.

The use of calcium based sorbents to remove SO_2 from the combustion products of coal and oil flames is not a new concept. Considerable effort was expended during the late 1960's and early 1970's to develop the dry limestone injection process. These activities were curtailed because sulfur capture was not particularly efficient and the injection of limestone caused considerable operational problems (e.g., fouling in the convective sections and plugging of the air heater). Recent studies in Germany indicate that this process could be a viable means of reducing SO_2 emissions if the sorbent is injected under low NO_x conditions. In the earlier studies, poor sulfur capture was attributed to thermal deactivation of the sorbent (deadburning) and poor sorbent dispersion throughout the boiler. It is possible that these problems could be overcome if the sorbent was injected with one of the air or fuel streams in a low NO_x burner. This would solve the problem of dispersion since all the fuel and air must mix if combustion is to be completed.

Thermal deactivation could be reduced because low-NO_x conditions minimize peak flame temperature. The objectives of the bench-scale studies described in this report were:

1. To determine whether the reduced peak flame temperatures and extensive fuel-rich zones typical of low-NO_x combustion conditions are conducive to sulfur capture by dry sorbent.
2. To determine the optimum time/temperature stoichiometry history of the sorbent for sulfur capture during coal combustion.
3. To determine whether captures reported in several pilot-scale tests are possible in the current boiler population.
4. To provide preliminary information on the imapct of calcium-based sorbents on boiler operability.

1.2 Approach

When the task was initiated, insufficient information was available to allow a complete definition of the bench-scale studies. The questions raised in previous experiments and the large number of process variables suggested that a phased approach was necessary. This method of planning and experimentation allowed the investigation of those processes and parameters which proved most important and enabled a selection of test conditions which would develop an understanding of the sulfur-capture process in the most cost-effective manner. The program organization is shown schematically in Figure 1-1. The task was initiated by conducting a series of program definition tasks in existing refractory tunnel furnaces, while at the same time a boiler simulator furnace (BSF) was being designed and constructed. The bulk of the experimental investigations were carried out in the BSF. Figure 1-1 shows that the BSF experiments were divided into three major categories, namely:

- A - Combustion Parameter Screening
- B - Thermal History/Sulfur Chemistry Studies
- C - Fuel and Sorbent Studies

The data from all of these experiments was used to plan the pilot-scale studies, carried out in other tasks of the same contract, and to define the

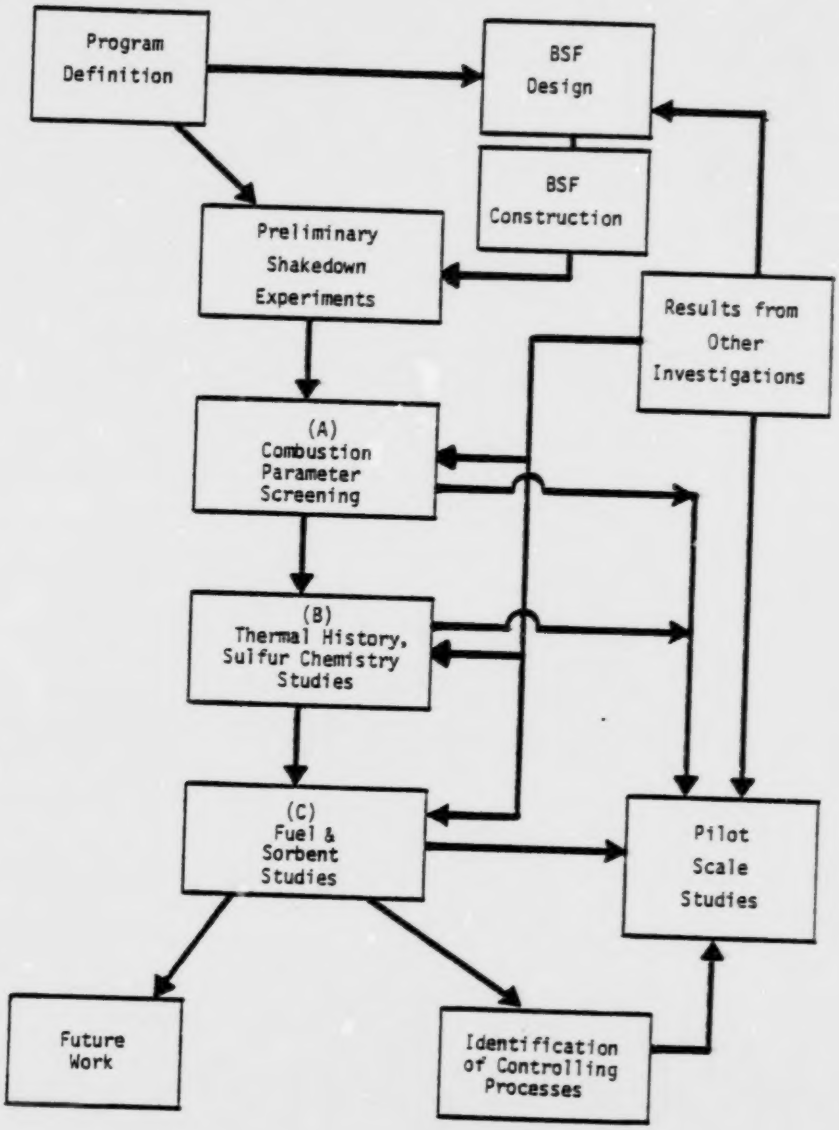
Program Definition
BSF Design
BSF Construction
Preliminary Shakedown Experiments
Results from Other Investigations
(A) Combustion Parameter Screening
(B) Thermal History, Sulfur Chemistry Studies
(C) Fuel & Sorbent Studies
Pilot Scale Studies
Future Work
Identification of Controlling Processes

Figure 1-1. Organization of bench-scale sulfur studies (Task 2.2).

needs for future experiments.

The BSF was constructed to simulate the thermal history of the products of combustion in a wide variety of pulverized coal fired boilers and was designed to satisfy the following criteria:

- independent control of wall temperature throughout the furnace and convective sections;
- fuel consumption rate nominally 80 lbs/hr;*
- accommodate various firing systems;
- variable preheat on all combustion air streams;
- simulation of particulate dropout throughout the radiant and convective sections;
- ability to rapidly and easily clean interior sections;
- potential for near adiabatic operation by minimizing heat loss;
- potential to extract heat at various locations;
- ease of access for sampling probes.

However, foremost in the design was the recognition that the times and temperatures experienced by the sorbent should cover as wide a range as possible to encompass those encountered in actual boilers. Figure 1-2 presents a schematic of the BSF system showing the sorbent and coal feed and air supply systems and the general arrangement of the furnace sections. The BSF was designed to simulate the various parts of a boiler. Thus the radiant furnace ① simulates the main heat release zone, the post-flame cavity ② , the region above the main heat release zone before the furnace exit, and air-cooled tubes simulate the superheater, reheat, and air heater sections of the convective pass ③ ④ .

1.3 Significant Results

Combustion Parameter Screening Studies (Series A)

The purpose of the screening experiments was to define the role of various combustion parameters in the sulfur capture process. The experiments were

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* See Conversion Table - Appendix C

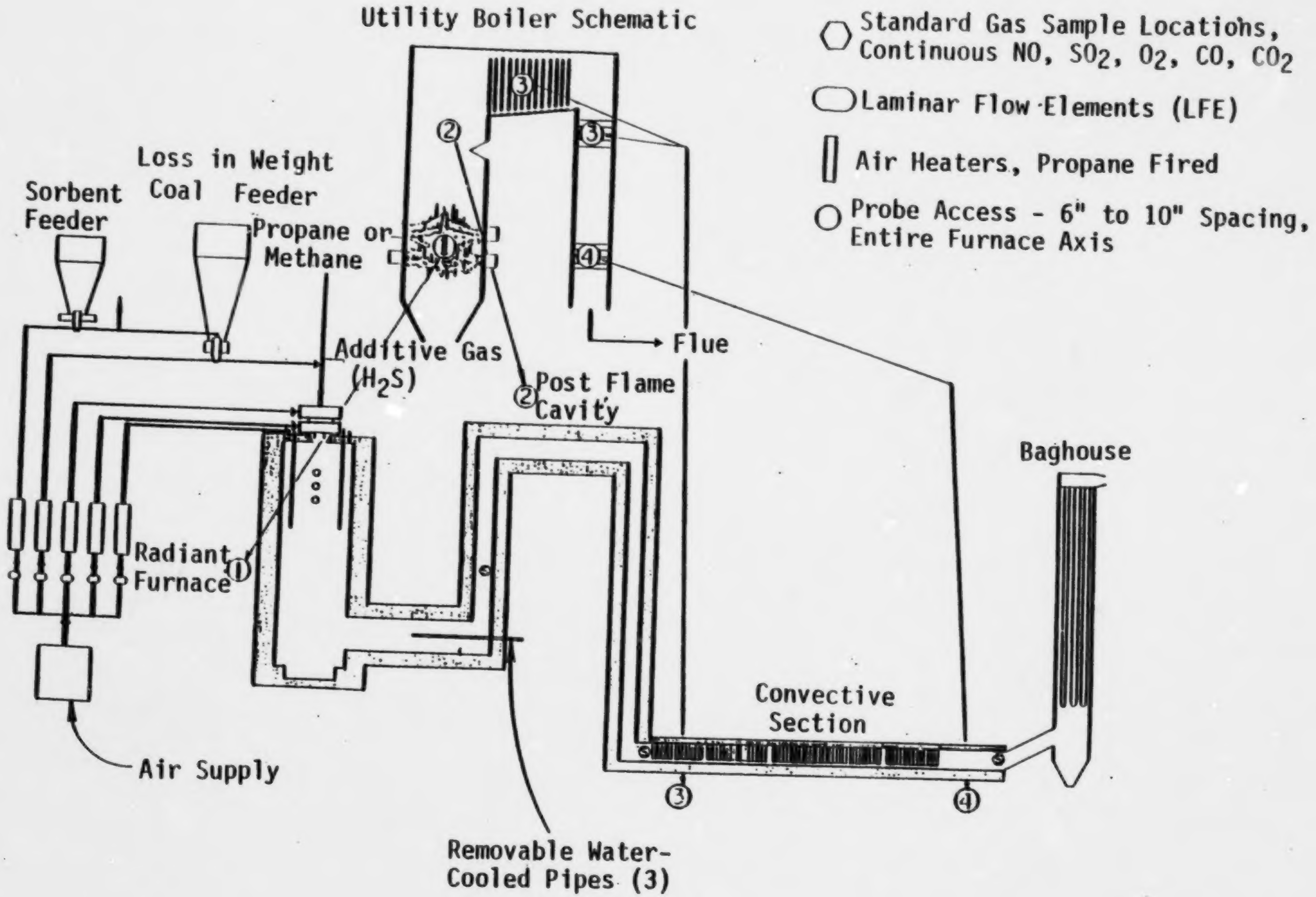

Utility Boiler Schematic
Standard Gas Sample Locations, Continuous NO, SO_2, O_2, CO, CO_2
Laminar Flow Elements (LFE)
Air Heaters, Propane Fired
Probe Access - 6" to 10" Spacing, Entire Furnace Axis
Loss in Weight Coal Feeder
Sorbent Feeder
Propane or Methane
Additive Gas (H_2S)
Post Flame Cavity
Flue
①
②
③
④
Radiant Furnace
Baghouse
Convective Section
Air Supply
Removable Water-Cooled Pipes (3)

Figure 1-2. Functional schematic of boiler simulator furnace.

conducted in two parts divided according to the method of combustion air staging used to simulate low NO_x combustion systems. The furnace could be staged in two ways: 1) Using a sub scale distributed mixing burner with onboard staging (tertiary) air ports at the burner fare. This is called burner or internally staged (A in Figure 1-3 and 2) firing the burner with a sub-stoichiometric amount of secondary air. Running the entire radiant section fuel-rich and adding the staging air at the base of the post flame section (B in Figure 1-3). This is called external or physical staging. In the first series of experiments (internally staged) a subscale distributed mixing burner was used and the parameters investigated included firing rate, heat extraction, burner zine stoichiometry, (stochiometry here is the ratio of actual air to theoretical required air.) excess air level, sorbent injection location (with the fuel or staging air), and staging air velocity. The second series of experiments (externally staged) were designed to investigate sulfur-capture under fuel-rich conditions using a system which provided for a relatively long (1-2 sec) residence time under fuel-rich conditions. In this second series of tests, the parameters investigated included firing rate, sorbent injection, heat extraction rate, rich zone stoichiometry, excess air level and tertiary air location.

The results of the parameter screening studies indicated that thermal environment had the major impact on sulfur capture by dry sorbents injected directly into the furnace. The burner staged experiments showed the influence of thermal environment most clearly; a reduction in peak furnace temperature due to cooling in the radiant furnace or to a reduction in load increased sulfur capture significantly. Changes in other parameters, such as sorbent location or injection velocity, had secondary effects on sulfur capture. The externally staged experiments indicated that sulfur capture was less dependent upon overall heat extraction rate than on the burner staged experiments.

One of the main points of interest in the parameter studies was to establish the importance of rich zone capture, since it was speculated that reactions involving reduced sulfur species (e.g., H_2S or COS) would produce higher sulfur captures than reaction with SO_2. Figure 1-4 shows the overall sorbent utilization as a function of the stoichiometry of the fuel-rich zone for coal and propane doped with H_2S to give the same exhaust SO_2 level. In

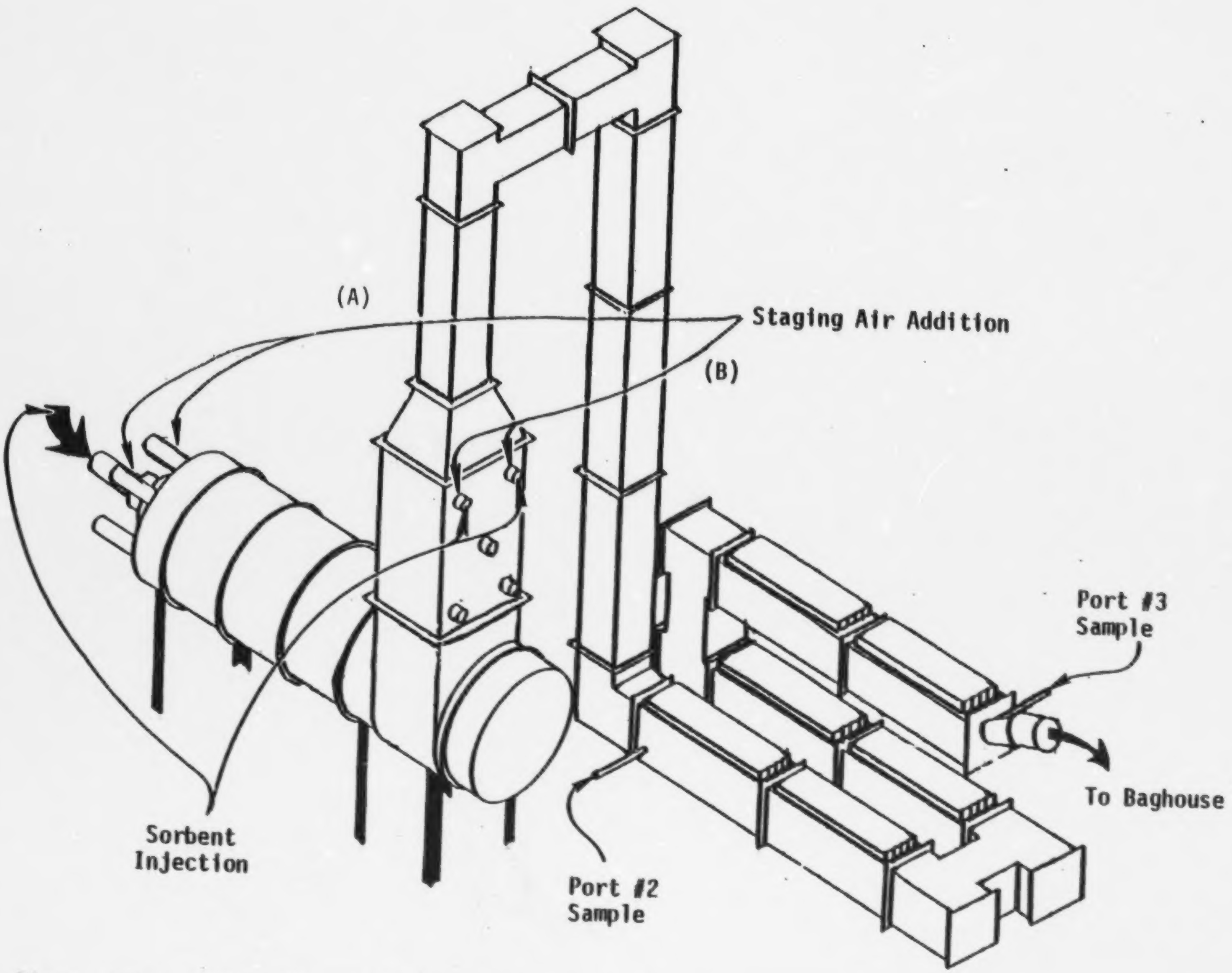

(A)
Staging Air Addition
(B)
Port #3
Sample
To Baghouse
Sorbent
Injection
Port #2
Sample

Figure 1-3. BSF configuration for internally (A) and physically (B) staged configurations.

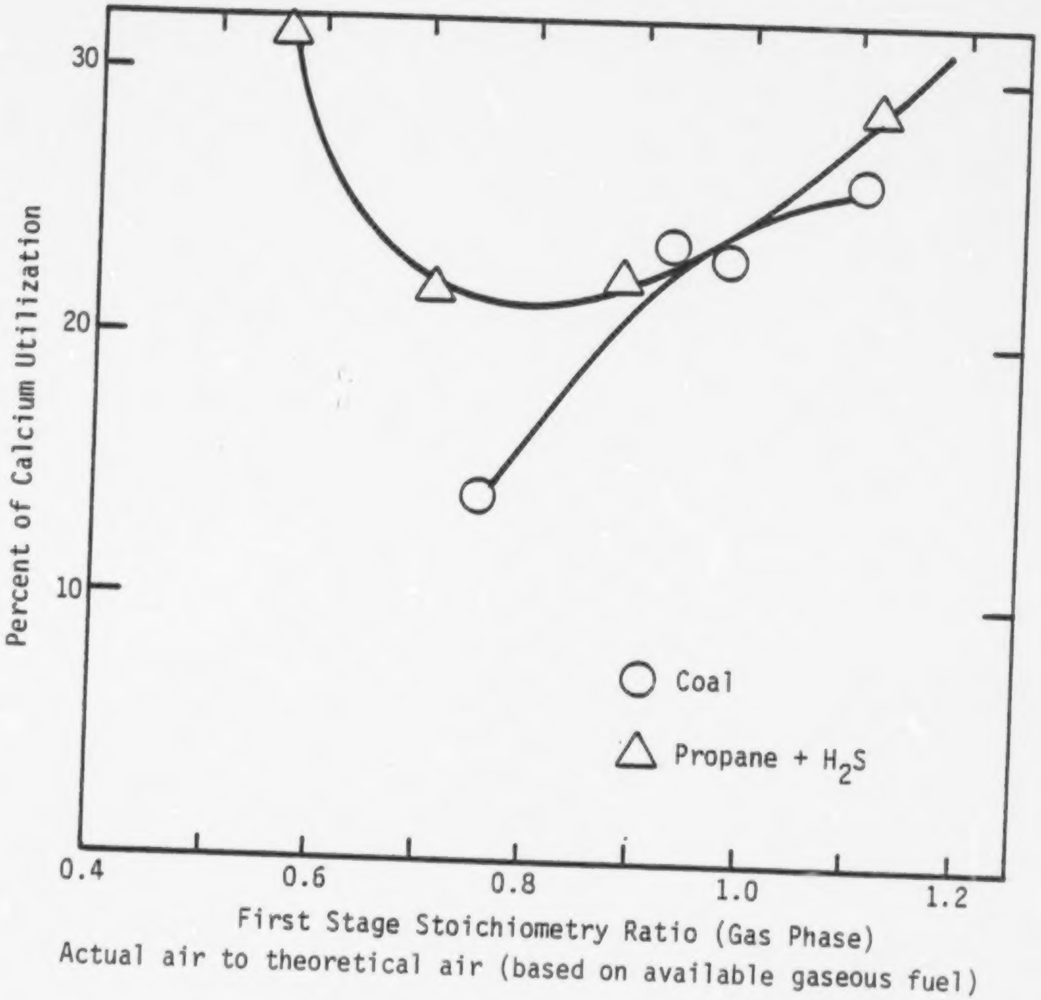


Figure 1-4. Capture and retention of sulfur under external staged conditions for coal and propane doped with H_2S, sorbent added with air at base of post flame section, uncooled.

this instance, the sorbent (Vicron) was added with air in the fuel-rich zone at the base of the postflame section. Rich zone stoichiometry is expressed in terms of the gas phase for both the gaseous and solid fuel. It can be argued that the difference in effectiveness with the two fuels is associated with the coal. Under fuel-rich conditions, much of the sulfur remains with the char and is not available for capture. When all sulfur is in the gaseous state, calcium utilization under fuel-rich conditions approaches 30 percent.

Sulfur Chemistry and Thermal Environment Studies (Series B)

The purpose of these experiments was to clarify the effect of thermal environment on sulfur capture by conducting two series of experiments:

- to investigate sulfur evolution and speciation in the fuel-rich zone of a staged combustion system;
- define the influence of a wide range of thermal environments on sulfur capture under both internal and external staged conditions.

The results from this series of tests can be summarized as:

- Under fuel-rich conditions, sulfur species appear to be far from equilibrium;
- even with gaseous fuels, sulfur capture in the fuel-rich zone does not appear to significantly impact the overall sulfur capture;
- with coal, capture in the fuel zone is limited because of the reduced sulfur driving force when a large fraction of the sulfur remains in the solid phase.

Fuel and Sorbent Effects (Series C)

The influence of fuel and sorbent properties on sulfur capture were investigated in the third and final series of small-scale experiments. The sorbent parameters which were varied, included particle size and composition. Sulfur capture was measured with a coal/water slurry and a lignite, as well as the baseline bituminous Indiana coal.

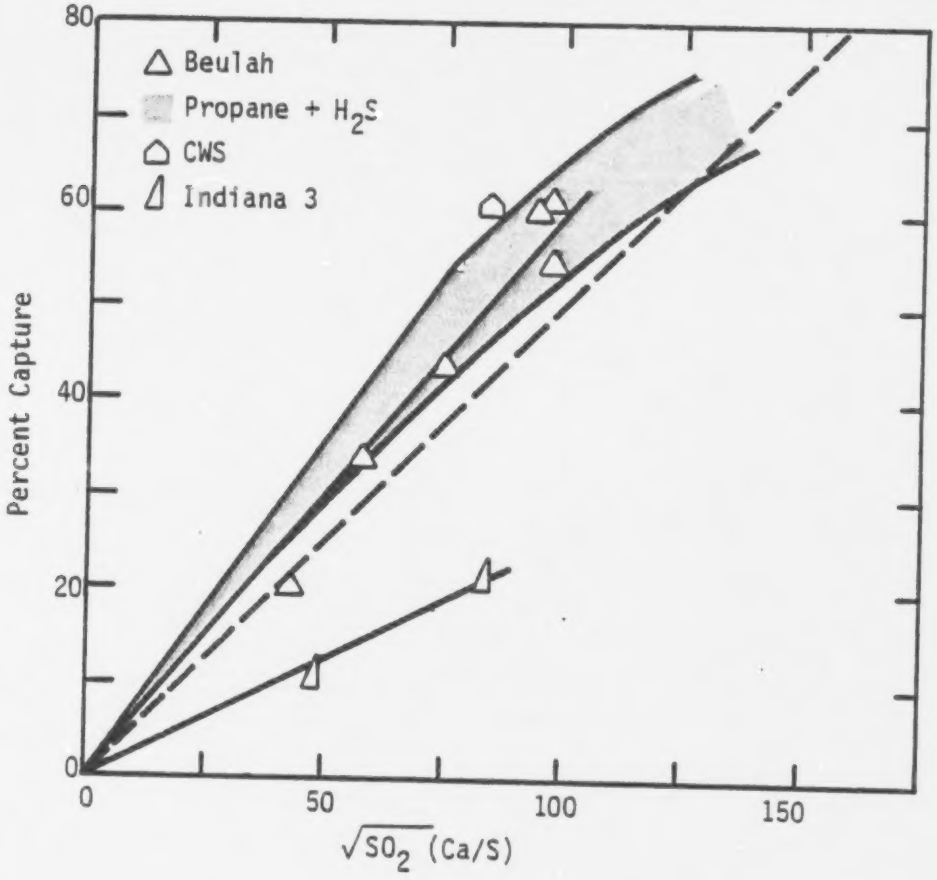


Figure 1-5. Effect of fuel on sulfur capture (Vicron 45-3).

Fuel Effects

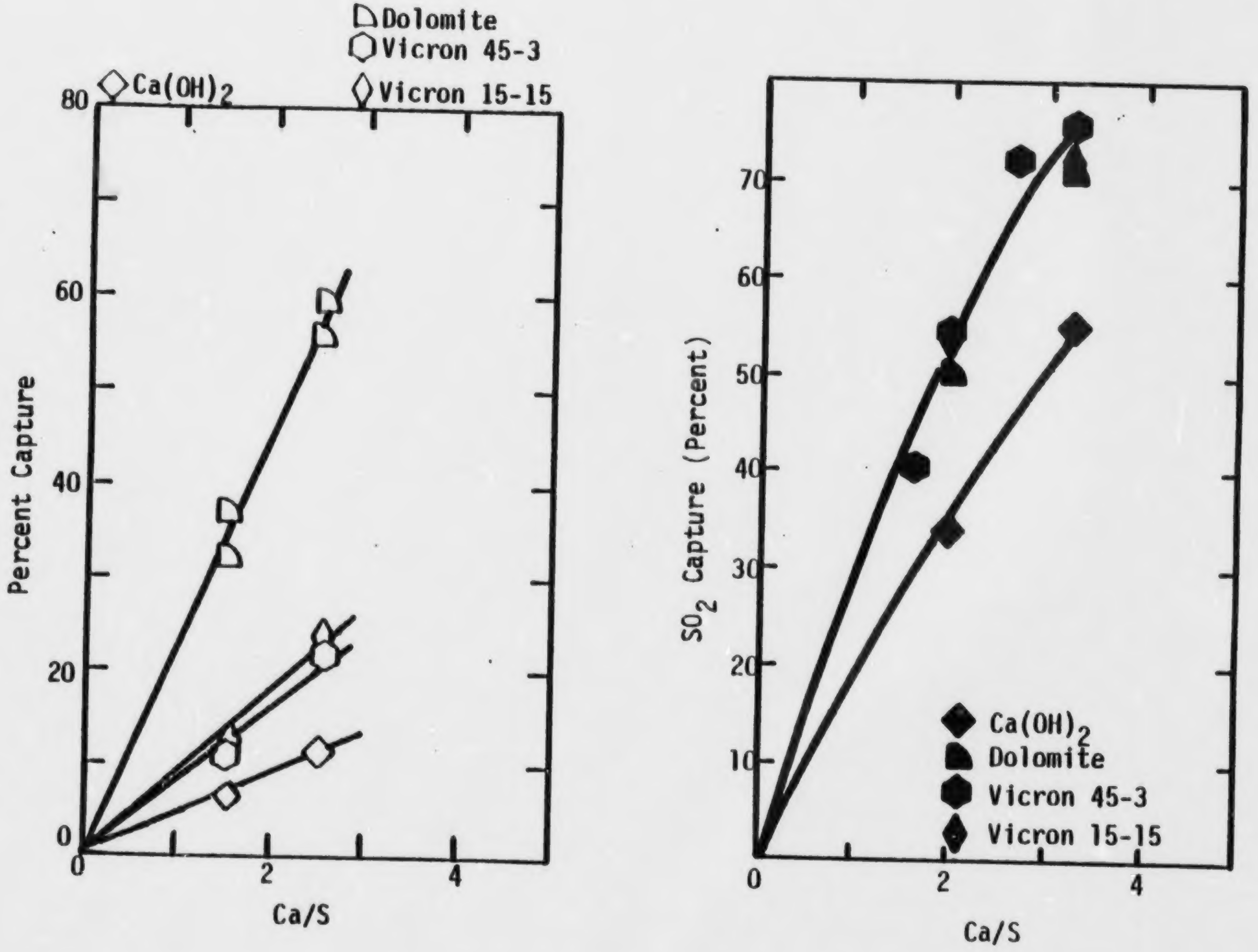
The effect of fuel sulfur on sorbent utilization was investigated by studying: Indiana (lot 3) coal, Beulah lignite (from North Dakota), propane doped with H_2S, and a coal/water slurry. All of the fuel screening tests were conducted with Vicron 45-3 as the sorbent and the boiler simulator furnace was fired with the distributed mixing burner. No cooling was added. Figure 1-5 compares sulfur capture for the four fuels investigated with one sorbent. The capture is worst with the Indiana coal and very similar for the lignite, doped propane, and the coal/water slurry. The dotted line shown in Figure 1-5 corresponds to 50 percent capture at a calcium-to-sulfur ratio of 2 with 2,500 ppm SO_2.(Which corresponds to about 2.5 % S in coal depending slightly on the fuel composition) The $\sqrt{S}$ x Ca/S parameter was used to help eliminate the effect of fuel sulfur content.($\sqrt{SO_2}$ dependance has been implied by fundamental work performed at Battell laboratories by Contant et. al.) The sorbent utilization was significantly less when the primary fuel was the Indiana coal than in all of the other cases tested.

Sorbent Effects

The influence of sorbent type on sulfur capture was studied at five different combustion conditions. Five sorbents were examined in these studies:

- Vicron 45-3
- Vicron 15-15
- Michigan Marl
- Hydrated Lime $Ca(OH)_2$
- Dolomite

These sorbents were tested with the Indiana three coal fired in the distributed mixing burner with and without external cooling, the Indiana three coal under externally staged conditions and using propane doped with H_2S in the distributed mixing burner. In general, the Dolomite gave good capture under all conditions examined. The hydrated lime appeared to be most sensitive to thermal environment while the Dolomite was least sensitive to changes in thermal environment. High captures were observed for all of the sorbents when the primary fuel was propane/H_2S. The influence of Sorbent type on sulfur capture



Indiana coal fired

Propane fired

Figure 1-6. Effect of sorbent on sulfur capture, Indiana coal and propane fuels.

was affected by the fuel. Dolomite gave significantly better capture than Vicron 45-3 with Indiana coal, but there was little difference when firing propane (see fig 1B). The size of limestone used (Vicron 45-3 at 11 μ m mesh and Vicron 15-15 at 3 μ m mesh) had little effect on sulfur capture with either Indiana coal or propane/H_2S.

1.4 Conclusions

The results of the experimental studies conducted in the boiler simulator furnace indicated that the parameters of major importance were thermal environment (including time-at-temperature) calcium-to-sulfur ratio, and sorbent composition. Thermal environment (local temperature) was shown to have a strong effect on the utilization of dry sorbents injected directly into the furnace. The burner staged experiments showed the influence of temperature most clearly; a reduction in peak flame temperature, due to cooling in the radiant zone or to a reduction in load, increased the sulfur capture significantly. Changes in other combustion parameters, such as sorbent location and injection velocity, had secondary effects on sulfur capture.

The effect of thermal history under physically staged conditions was less definitive. Changes in both load and thermal cooling in the radiant furnace were complicated by the changes in furnace temperature due to the physical staging itself, since physically staging the coal flame significantly altered the furnace temperature profile. With external staging near stoichiometric conditions, the first (fuel-rich) stage, which included the entire radiant furnace, and the second stage region (the first part of the post-flame cavity) were hotter than under burner-staged conditions. First stage stoichiometry and sorbent location both influenced sulfur capture under externally staged conditions; however, the results suggest that these influences may be more strongly related to thermal changes than to chemical changes. Further, the data do not support the concept that sorbent utilization is much higher under fuel rich conditions.

The differences in capture with different sorbent types was influenced by combustion conditions and the fuel used. Of the sorbents tested Dolomite gave the highest capture. The hydrated lime was the most sensitive to changes in thermal conditions. Little effect of sorbent particle size in the range tested (11 to 3 μ m) was observed.

The effect of fuel type on sulfur capture was greater than expected. Of the fuels tested: Indiana and Beulah coals, a coal water slurry and propane doped with H_2S, the Indiana coal gave the lowest capture. Adiabatic flame temperatures were calculated for all of the fuels at stoichiometric ratios from 0.6 to 1.2. The calculated temperatures for the solid fuels rank in the same order as the sulfur capture obtained; the highest sorbent utilization was achieved with the fuel producing the lowest theoretical temperature. However, the differences in calculated temperature do not appear to be significant enough to explain the large differences in capture. The data strongly suggest that the difference between the relatively poor sorbent utilization with the Indiana coal and the excellent sorbent utilization with the propane/H_2S cannot be solely attributed to thermal effects.

The observed effect of fuel type needs further investigation to determine the cause of differences in capture. Other areas which need further exploration are fuel/sorbent interactions, the effect of particle size over a greater range and with different sorbents. The effect of sorbent injection location at positions other than the burner fuel and of sorbent surface area (and the effect of temperature on sorbent surface area).

2.0 INTRODUCTION

Although coal is the most abundant source of fossil fuel energy in the United States, its use poses several serious problems for society. Mining coal, either from deep or surface mines, involves environmental, safety, and health considerations. Once coal is mined, problems associated with transportation, storage, and energy conversion must be faced. Coal is used primarily for the generation of electricity in thermal power plants which burn coal in suspension after it has been pulverized. Coal is not a pure hydrocarbon and the impurities cause the generation of atmospheric pollutants when it is burned. Assuming an efficient combustor, atmospheric pollutants are produced from the impurities in coal: nitrogen, sulfur, and inorganic material. The inorganic material forms fly ash, the major portion of which exits the boiler and must be removed from the exhaust stream in a precipitator or baghouse. Nitrogen and sulfur give rise to oxides (NO, NO_2, SO_2, SO_3) which are themselves pollutants, and which contribute to the acid rain problem, since they are the precursors of nitrates and sulfates.

There are four different approaches to the problem of reducing the emission of sulfur and nitrogen oxides resulting from the combustion of pulverized coal, namely:

1. Removal of the offending species from the coal. Nitrogen and some of the sulfur is bound in the organic coal matrix. Therefore, physical cleaning techniques which reduce coal ash levels reduce coal sulfur concentrations by virtue of removal of pyrite, but have minimal impact upon coal nitrogen content. Conversion of the solid fuel into clean gaseous or relatively clean liquid fuels are potentially more effective albeit more costly methods for reducing both fuel bound sulfur and nitrogen.
2. Removal of the pollutant species from the products of combustion. Flue gas treatment techniques are available to remove both nitrogen and sulfur oxides before the products of combustion are emitted into the atmosphere. Although available, these techniques increase the complexity of power plants and the cost of power generation.

3. Fuel blending. Total sulfur oxides emissions can be reduced by mixing high and low sulfur fuels. Examples of this approach are coal oil mixtures and coal blending.

4. Prevention of the formation of gaseous pollutants. Nitrogen oxide emissions can be reduced by limiting flame temperatures and controlling oxygen availability in the initial heat release zone of the combustor. Sulfur oxide emissions can be reduced by retaining sulfur in the solid phase and removing it with the solid effluent.

This report describes a series of experiments which were designed to provide information on this final approach - the use of sorbents to reduce SO_x emissions under combustion conditions which also minimize NO_x formation.

Nitrogen oxide emissions from pulverized coal fired power plants are due primarily to the oxidation of fuel bound nitrogen, which is partitioned between the volatile and char fraction when the coal is decomposed. It is well-known that the fractional conversion of gaseous nitrogen species (XN) to NO is controlled by oxygen availability because of two completing reaction paths:

1. Oxidizing $XN + \ldots \longrightarrow NO + \ldots$

2. Reducing $XN + \ldots \longrightarrow N_2 + \ldots$

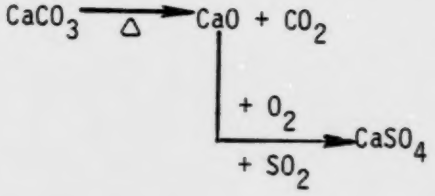
In addition, there is an optimum gas phase stoichiometry (approximately 70 percent theoretical air) which maximizes N_2 production by the second path. In contrast, much less is known about the oxidation of nitrogen in the char, other than that under oxidizing conditions, conversion to NO is low but finite. Nitrogen oxides are also formed by the fixation of molecular nitrogen. This formation path can be restricted by limiting flame and bulk gas temperatures, since the rate of fixation is very strongly dependent upon temperature. Thus, nitrogen oxide formation in pulverized coal flames can be reduced by modifying the combustion process to ensure that the coal reacts initially in an oxygen deficient region and that peak flame temperatures are limited. This can be achieved by dividing the furnace so that combustion takes place in two stages; a fuel rich (reducing) stage in the first zone and a fuel lean (oxidizing) region in the second, or burnout, zone. An alternative approach, and one that is being supported by the EPA, uses burner design and outboard staged air ports to provide a flame with a fuel rich inner core surrounded by an oxidizing envelope. The two methods of staging may be called furnace or external staging and burner or internal staging, respectively.

Sulfur oxide emission from pulverized coal fired power plants are due to the oxidation of both organic (fuel bound) and inorganic sulfur. It is known that the sulfur in the fuel does not necessarily convert quantitatively to SO_2/SO_3 in the combustion products. Coals with high alkali metal oxides contents are known to retain significant amounts of sulfur as sulfates in the ash. Therefore, increasing the alkali metal content of the fuel by mixing a sorbent with the fuel either prior to or during combustion may increase the retention of the sulfur in the solid phase and, therefore, reduce SO_2 emissions because some of the sulfur will be removed in the particulate collector as a solid.

2.1 Background, Furnace Injection of Dry Sorbents

The use of sorbents to control the emissions of sulfur oxides from coal fired power plants is not a new concept. Considerable effort was expended on the investigation of the process during the late 1960's and early 1970's. The results of these investigations and of some more recent studies are reviewed in this section.

The injection of alkali sorbents into a combustor for the control of SO_2 emissions is a conceptually simple process. A pulverized sorbent, generally limestone ($CaCO_3$), is injected into the combustion chamber of a boiler where it flash-calcines to lime (CaO) and at the same time begins to react with sulfur dioxide (SO_2) and oxygen (O_2) to form calcium sulfite ($CaSO_3$) and/or calcium sulfate ($CaSO_4$). The overall reaction mechanism is believed to be:


$$CaCO_3 \xrightarrow{\Delta} CaO + CO_2, \quad CaO \xrightarrow[+\,SO_2]{+\,O_2} CaSO_4$$

Extensive research into the process has been done in Germany, Japan, Poland, Czechslovakia, and the United States. Despite the fact that these investigations were carried out under experimental conditions involving different furnace and reactor types, additives, injection variables and operating conditions, there is considerable agreement in the results obtained. Figure 2-1 shows the range of SO_2 removal for both pilot and plant scale experiments reported in these early studies (after Gartrell, 1973). The sorbent was either hydrated lime or hydrated dolomitic lime. The range of conditions resulted from the use of different boilers, different injection locations, etc. The parameters that were found to affect the adsorption efficiency of injected sorbent were:

- those properties of the sorbent that affected the degree of porosity after calcination;
- particle size and surface area;
- temperature at the point of injection;
- retention time;
- limestone distribution in the combustion gases;
- mass transfer between SO_2 in the flue gas and sorbent particles;
- SO_2 concentration;
- furnace operating conditions;
- sorbent feed rate (Ca/S ratio).

It can be seen that the range of sulfur capture in pilot and bench scale tests was wider than the captures obtained in plant scale tests.

Figure 2-1 highlights data from three different operating boilers. The Shawnee Steam Plant is a wall fired pre-NSPS boiler which was the site of the EPA demonstration conducted by the TVA. The Wisconsin Electric Company plant is a down fired unit and the Detroit Edison plant is a corner fired unit. Point 4 represents captures obtained in a brown coal fired boiler operated by RWE in West Germany. The sorbent was mixed with the fuel in the Wisconsin, Detroit Edison, and RWE tests. In the Shawnee tests the sorbent was injected from the back wall above the burner level. (Other injection locations at Shawnee gave lower captures.)

The TVA tests were not encouraging. SO_2 removal of only 18 percent was reported for two times stoichiometric (sorbent/sulfur) at full load when a limestone was used as the sorbent. When the firing rate was reduced to half

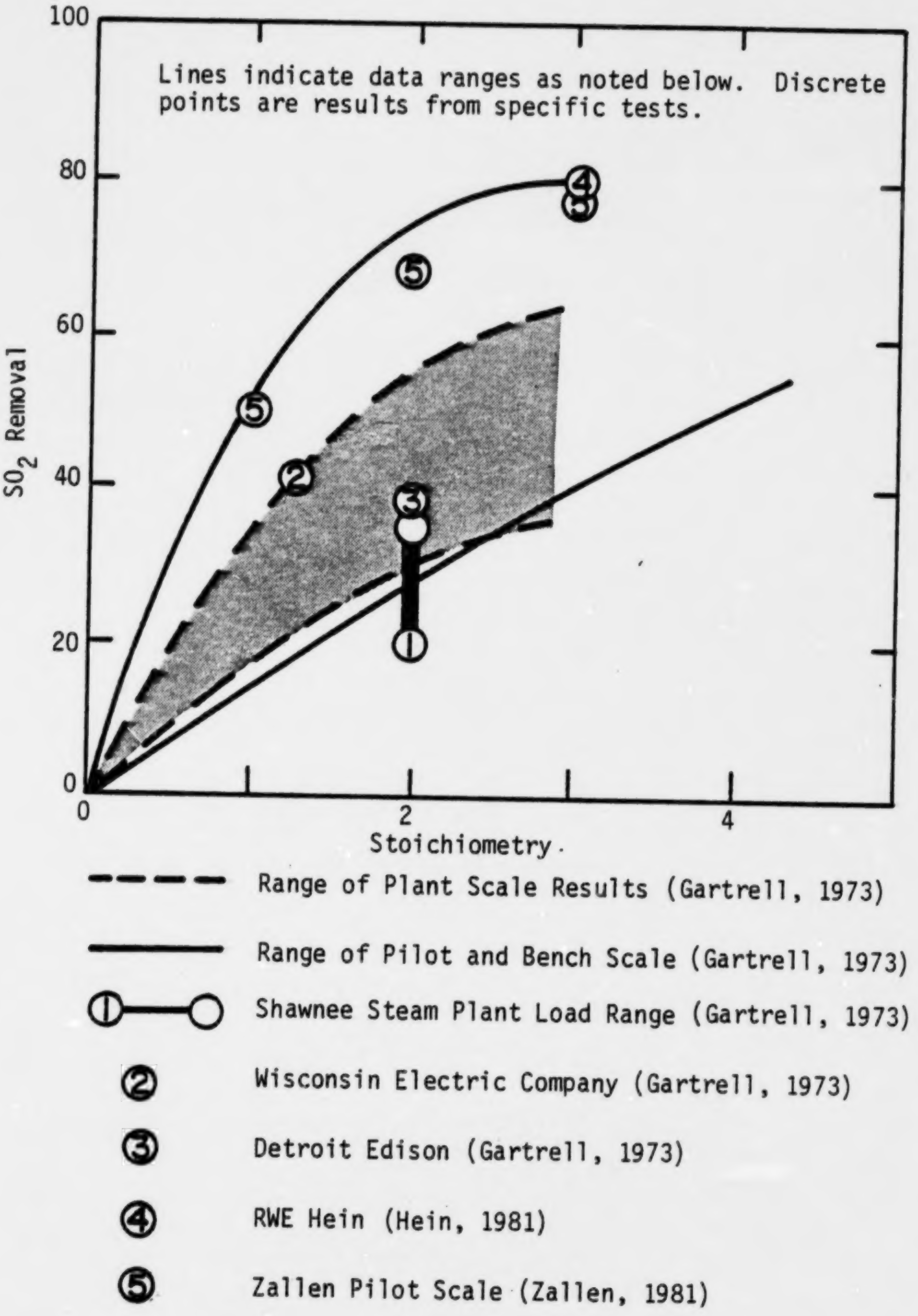


Figure 2-1. Range of SO_2 removal reported for plant, pilot, and bench scale studies with sorbent addition.

load an 8-point increase in sulfur removal was observed. Maximum captures of 36 percent at two times stoichiometric were reported for marl injected at half load firing. SO_2 removal was significantly better when the sorbents were injected at higher furnace elevations where the gas temperatures were lower. Long term testing could not be carried out because of excessive pressure drops in the reheater caused by ash deposits. Limestone/fly ash deposits on the reheater grew rapidly and were of a composition that defied removal. Increased soot blowing frequency could not prevent plugging of the reheater. The poor performance at Shawnee was attributed (Gartrell, 1973) to a combination of:

- deactivation of the sorbent due to deadburning;
- inadequate mixing of the sorbent with the combustion products at temperatures appropriate for the sulfation reaction;
- generation of SO_2 due to decomposition of the sulfate.

The data for the down fired boiler shows better capture than that obtained in the TVA unit (which is front wall fired). In a down fired boiler the heat release is delayed by reducing the rate of fuel/air mixing and the primary coal transport stream has a lower fraction of the combustion air than is normally used in wall fired units. In these tests, the additive was injected with the coal. Improved SO_2 removal in this particular boiler may be attributed to a combination of reduced combustion intensities or the residence time experienced by the sorbent under fuel rich conditions because it was injected with the coal. Corner fired units such as that tested at Detroit Edison have some of these same characteristics (spread out heat release and longer residence times at fuel rich conditions). The capture values reported for the corner fired unit tests are also higher than those reported for the wall fired (TVA study) unit.

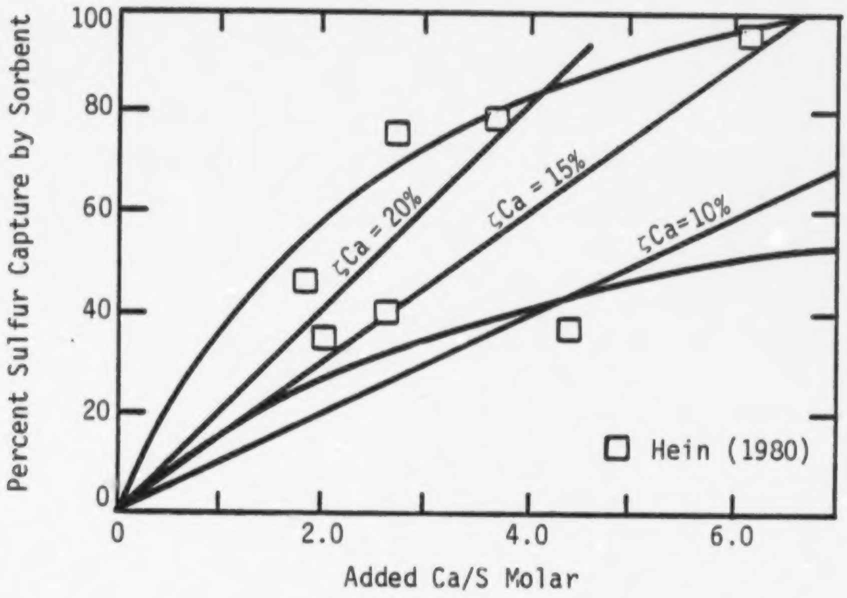
The results of these early studies were rather disappointing and little work on the direct injection of dry sorbents into pulverized coal-fired furnaces was performed for several years. Renewed interest in the process is the result of other investigations started in the late 1970's, which demonstrated better sulfur captures using different combustion systems: low NO_x systems (Zallen, et al, 1981) and brown coal fired systems (Hein, et al, 1981).

Hein and co-workers (1981) of RWE in West Germany are conducting an extensive research program on the use of calcium-based sorbents to reduce sulfur oxide emissions from power plants burning Rhinish brown coals. Tests carried out in a 175-ton-of-steam/hr boiler indicated that the natural sulfur retention ability of the brown coal could be improved by blending sorbent with the fuel before the coal pulverizers. Rhinish brown coals contain approximately 60 percent moisture as mined, and this leads to large flue gas volumes and low bulk furnace temperatures. Sulfur concentrations in the coal are typically less than 0.5 percent on an as-received basis and calcium concentrations as high as 0.7 percent are common. The addition of calcium to the coal feed was tried as an SO_2 emission control strategy, with variable success depending upon the sorbent type and the Ca/S ratio in the coal before sorbent addition. Figure 2-2a shows data obtained for various levels of calcium carbonate addition. The data in Figure 2-2b show SO_2 reductions obtained by the addition of various sorbents. Hein attributes the relatively high captures obtained to the low furnace temperatures characteristic of brown coal firing.

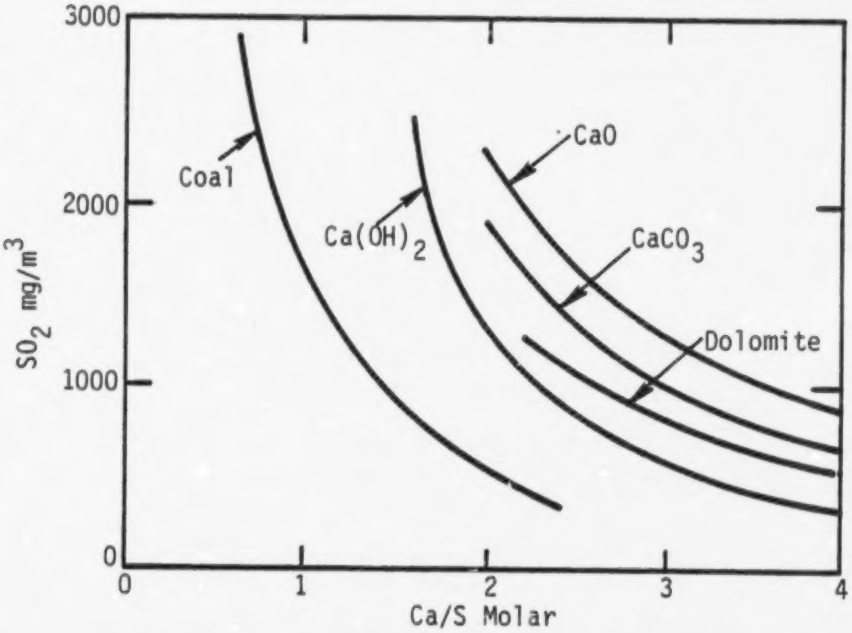
The data reported by Zallen et al (1979) were obtained in pilot scale tests of an EPA distributed mixing burner. The tests were carried out in a test furnace operated at 50 to 75 percent of full capacity. The sorbent was batch-mixed with the coal prior to the pulverizer and injected into the furnace with the coal. The sorbent must have experienced maximum furnace temperatures since it had to pass through the flame zone. However, the captures reported by Zallen are extremely good (see Figure 2-1). These results introduced the conjecture that low NO_x combustion conditions are conducive to sulfur capture by dry sorbents.

Steinmüller has a low NO_x burner arrangement very similar to that developed by the EPA. Recent tests conducted with a sub-scale burner by the International Flame Research Foundation in Holland have indicated that this burner can be used with additive injection to reduce SO_2 emissions. Parameters investigated in these studies included:

- Fuel - natural gas mixed with SO_2, three different coals, heavy fuel oil, and solid oil pitch;
- Sorbent - calcium hydroxide, calcium carbonate and activated calcium hydroxide;



a. Sulfur Reduction with Added $CaCO_3$



b. Additive Injection, General Correlations

Figure 2-2. Sulfur emissions and calcium based additives for German brown coal (Hein, 1981).

- Stoichiometry - molar ratios of calcium-to-sulfur of 1 to 4;
- Injection location - either with the fuel, the staged air, or into the external recirculation zone;
- Degree of burner staging;
- Furnace operating conditions, particularly firing rate.

Figure 2-3 summarizes the results of some of these studies, calcium hydroxide was the sorbent. The experiments were conducted in a refractory furnace with an exit temperature of 1100°C (2010°F). Sulfur captures in excess of 60 percent are reported at calcium-to-sulfur ratios of two. This is similar to the data reported by Zallen, et al (1981), but considerably better than has been obtained in an operating boiler. Sulfur captures obtained with the Steinmuller low NO_x burner increased with increasing fuel sulfur content for the same fuel. The different captures reported for coal and doped natural gas was surprising. Reported sulfur captures obtained with a 2.42 percent sulfur coal are twice those that would be obtained in a natural gas flame doped to give similar content. Fundamental studies (Coutant, 1981), carried out in a gas-fired, plug-flow reactor indicate that sulfur capture increases linearly with calcium-to-sulfur ratio at stoichiometries less than 3-4. Percent capture was also found to be proportional to the square root of the local SO_x concentration. A fuel effect was not reported. The most reasonable explanation for the observed fuel effect is that the two fuels exhibit differences in peak flame temperatures and radiative characteristics; therefore, the sorbent experiences a very different thermal history in the two flames.

Summarizing the early seventies, attempts to control SO_x emissions by the injection of dry sorbents proved to be unsuccessful, but recent pilot-scale data suggests that operation under low NO_x conditions could improve the SO_2 capture efficiency of calcium-based sorbents, therefore, a research and development program designed to investigate the use of dry sorbents to capture sulfur from pulverized coal flames under low NO_x conditions was instituted. Questions addressed included:

1. Are the reduced peak flame temperatures and extensive fuel-rich zones typical of low NO_x combustion conditions conducive to sulfur capture by dry sorbents?

Fuel Type	Sulfur Content
Blumenthal (Coal)	2.42%
Auguste Viktoria (Coal)	1.09%
Göttelborn (Coal)	0.8 %

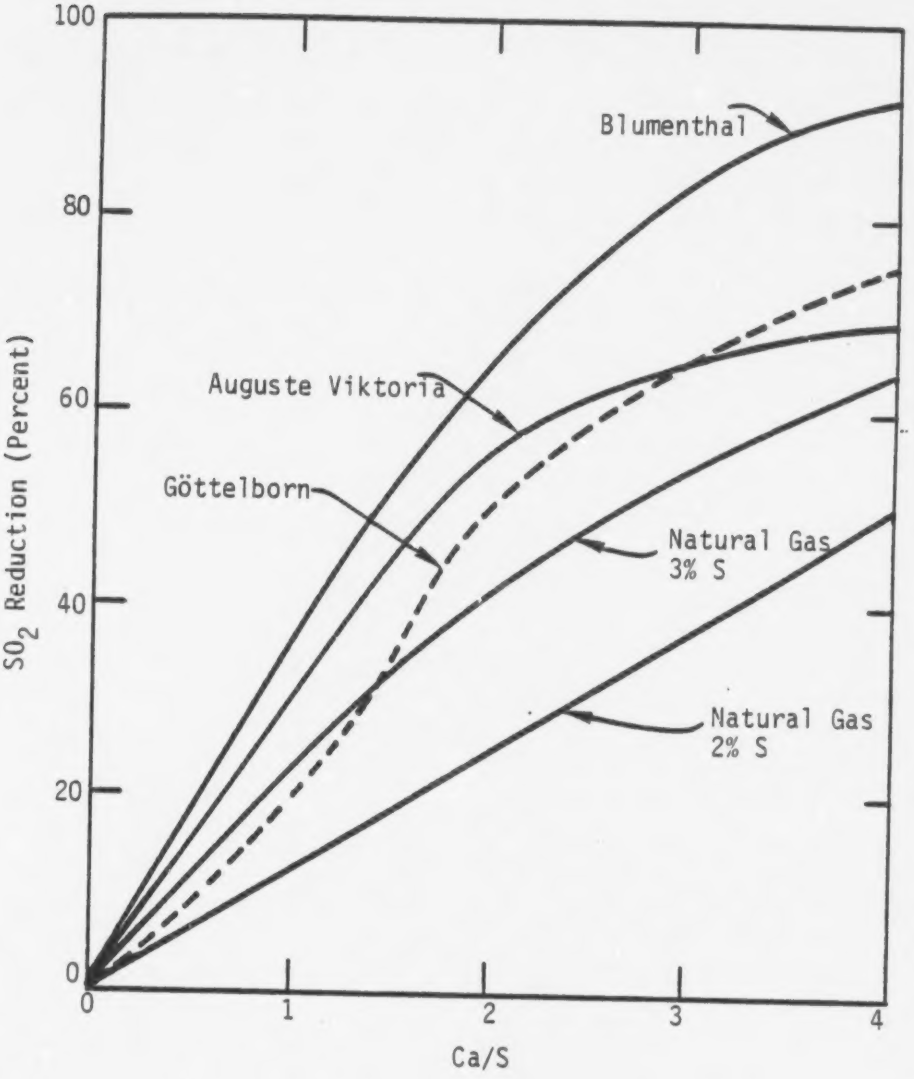


Figure 2-3. Summary of results obtained with the Steinmüller burner in the IFRF furnace, optimum conditions, "activated" $Ca(OH)_2$ as the sorbent.

2. What is the optimum time/temperature stoichiometry history for sulfur capture by a sorbent during coal combustion?
3. Can the captures reported in pilot scale tests be achieved in existing boilers?
4. What is the impact of the injection of calcium-based sorbents on boiler operating ability because of slagging, fouling, and increased solids loading?

This report presents data from bench-scale studies designed to investigate these questions.

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Hein, K.R.G., W. Glasser. "Dry Additive Process for SO_2 Removal During the Combustion of Brown Coals", International Flame Research Foundation, Sixth Members Conference, Noordwykerhout, May 1980.

Zallen, D.M., R. Gershman, M.P. Heap, W.H. Nurick. "The Generalization of Low Emission Coal Burner Technology", Proceedings, Third Stationary Source Combustion Symposium, Volume II, EPA-600-7-79-0506, p 73, 1979.

3.0 PROGRAM ORGANIZATION

The purpose of the bench scale studies discussed in this report was to establish and quantify those parameters which affect the capture of sulfur by solid sorbents. The work was directed toward the investigation of sorbent injection into combustion systems designed to reduce NO_x emissions. Because the questions raised by earlier investigations of direct sorbent injection for the control of SO_2 were so broad and the number of possibly important parameters was large, a phased screening approach was used. Insufficient information was available at the onset of the project to plan the complete test sequence in detail; therefore, the results of one set of experiments were used to plan the next set of experiments. This method of planning and experimentation allowed the investigation of those processes and parameters which proved most important and enabled the selection of test conditions to give the best information base. The program organization is shown schematically in Figure 3-1.

3.1 Program Definition Experiments

This project required the design and construction of a new facility. In order to provide input into the required capabilities of the new furnace and to establish an information base for the planning of the experiments in the new facility, experiments were conducted in three already existing furnaces. These three furnaces were all downfired refractory tunnel furnaces firing at 70,000 to 100,000 Btu/hr. The new furnace, designed to simulate the thermal history of particles in a boiler and, therefore, named the Boiler Simulator Furnace (BSF) fired at a rate of 1,000,000 Btu/hr. The experiments performed in the small-scale facilities (the program definition experiments) were designed to investigate several parameters including:

- Sorbent Effects
  - Composition
  - Particle Size
  - Ca/S Ratio
- Flame Effects
  - Excess Air Level

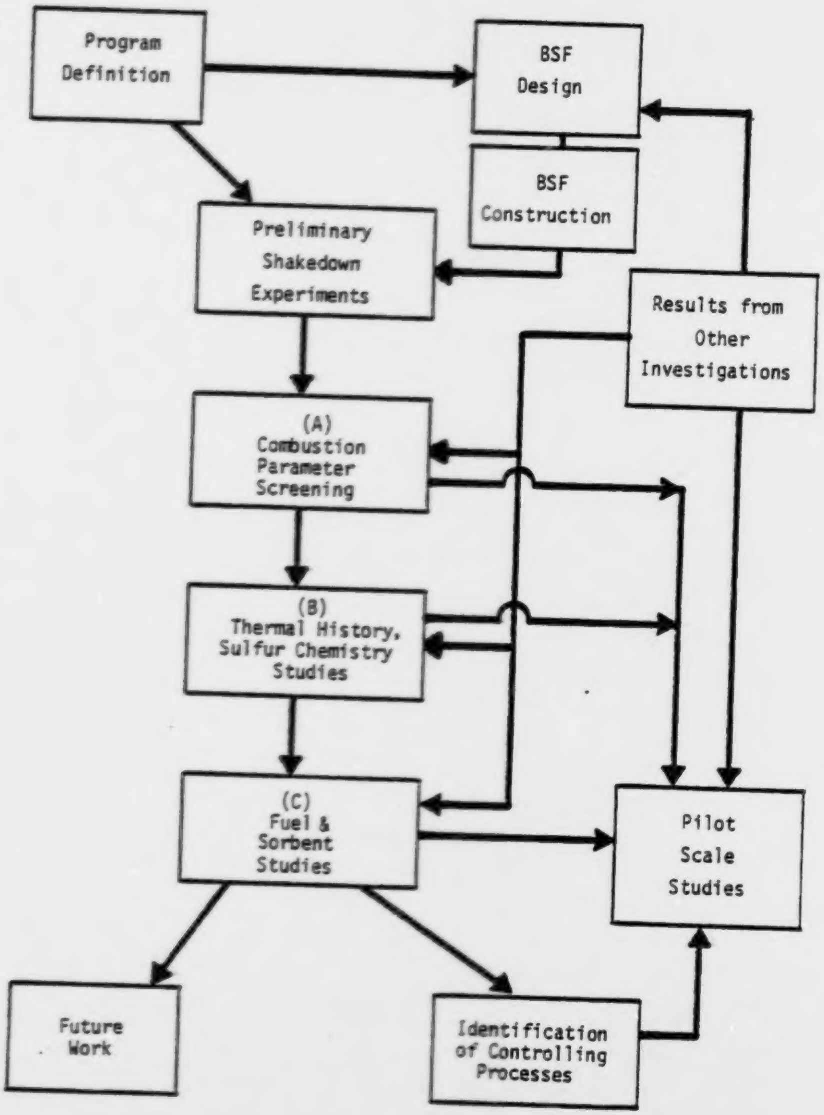

Program Definition
BSF Design
BSF Construction
Preliminary Shakedown Experiments
Results from Other Investigations
(A) Combustion Parameter Screening
(B) Thermal History, Sulfur Chemistry Studies
(C) Fuel & Sorbent Studies
Pilot Scale Studies
Future Work
Identification of Controlling Processes

Figure 3-1. Organization of bench scale sulfur studies (Task 2.2).

  - furnace load
- Sulfur (fuel) Effects
  - sulfur species oxidation state
  - SO_2 concentration

The results of these experiments were not conclusive but did help determine test conditions for study in the BSF and helped define the scope of the combustion parameter screening studies. The new facility had to be characterized before extensive experimentation was performed. During the furnace shakedown and characterization some sorbent injection experiments were performed. The results of these experiments were used along with the results of the program definition studies to plan subsequent testing.

3.2 Combustion Parameter Screening Studies (Series A)

The program definition experiments and results from other investigations had identified a number of combustion parameters which affect sulfur capture by dry sorbents. The purpose of the parameter screening experiments was to define the role of some of these parameters in the sulfur capture process. The experiments were performed in two sets. The sets were divided on the basis of the method of combustion air staging used to simulate low NO_x systems. The first set of experiments (internally staged) were designed to investigate sulfur capture under predominantly fuel-lean conditions using a sub-scale distributed mixing burner. Parameters investigated included: firing rate, cooling, burner zone stoichiometry, excess air level, sorbent injection location, and tertiary air velocity. The second set of experiments (externally staged) was designed to investigate sulfur capture under fuel-rich conditions using a system which provided long (1-2 second) residence times under fuel-rich conditions. The effect of parameters such as: firing rate, sorbent location, cooling, rich-zone stoichiometry, excess air level, and tertiary air location were investigated. The effect of first-state (rich zone) stoichiometry on sulfur evolution from the coal under fuel-rich conditions was also studied.

3.3 Sulfur Chemistry and Thermal Environment Studies (Series B)

The combustion parameter screening studies (Series A) provided data clarifying the effect of several parameters on sulfur capture and posed some new questions about the sulfur capture process. A series of experiments (Series B) investigating phenomena observed in Series A and further clarifying the effect of the thermal environment on sulfur capture were performed. This phase of the program also had two major parts. The first was designed to further investigate sulfur evolution and specieation in the fuel-rich zone and the second was designed to define the effect of several thermal environments on sulfur capture. Both internally (burner staged) and externally (physically) staged conditions were investigated.

3.4 Fuel and Sorbent Effects (Series C)

The final experimental phase of the bench-scale program was the investigation of fuel and sorbent effects. The results of the first two studies were used to select test parameters which would provide a comprehensive, rigorous set of conditions for sorbent parameter screening. Series A and B results and a review of the available literature were used to select both fuel and sorbent characteristics for investigation. Sorbent parameters which were varied in these studies included: particle size, form (calcite, marl), composition (limestone, dolomite, and hydrated lime), and surface area. Fuel characteristics which were investigated included: ash content and composition, heating value, sulfur content, and water content.

The final phase of the bench-scale program was the formulation of conclusions from the data, the identification of the processes which control sulfur capture, and the definition of unanswered questions which require further investigation.

4.0 PROGRAM DEFINITION EXPERIMENTS

The design of an experimental program to clarify the processes which control sulfur capture by dry sorbents under low NO_x conditions required some definition of the scope of work and an assessment of promising lines of inquiry. A literature review, equilibrium calibrations, measurements of inherent sulfur capture (from earlier experiments), and preliminary experiments in small-scale gas and coal-fired furnaces were used to help define the scope and direction of the experimental bench-scale studies. The program definition work was also used to help define design criteria for the new experimental facility, the boiler simulator furnace. This section describes results from the equilibrium calculations and data from inherent capture and program definition experiments.

4.1 Equilibrium Calculations

Figures 4-1 and 4-2 show typical results of equilibrium sulfur species distribution calculations for propane/air/SO_2/$CaCO_3$ mixtures at various temperatures. Figure 4-1 shows fuel-lean distributions, and Figure 4-2 shows fuel-rich conditions. These calculations were also performed for a lignite coal with similar results (see Figures 4-3 and 4-4). The equilibrium calculations indicate that solid sulfur-containing compounds are expected to decompose at flame temperatures, $CaSO_4$ being stable to temperatures around 2000°F at SR = 1.1 and CaS being stable up to 2700°F at SR = 0.75.

The temperatures at which 50 percent of the sulfur may be found in the condensed phase at equilibrium for several coals and for propane are plotted against stoichiometric ratio in Figure 4-5. These results indicate that the solid phase is more stable under fuel-rich conditions. Caution should be exercised in the interpretation of these results as equilibrium calculations do not adequately reflect the chemical kinetics actually occurring in a flame. The sharp drop in decomposition temperature at SR = 1.0 may be a product of the rapid change in oxygen availability around SR = 1.0. It is not clear from equilibrium calculations what conditions favor the formation of $CaSO_4$ rather than CaO and SO_2 from CaS when going from reducing to oxidizing conditions.

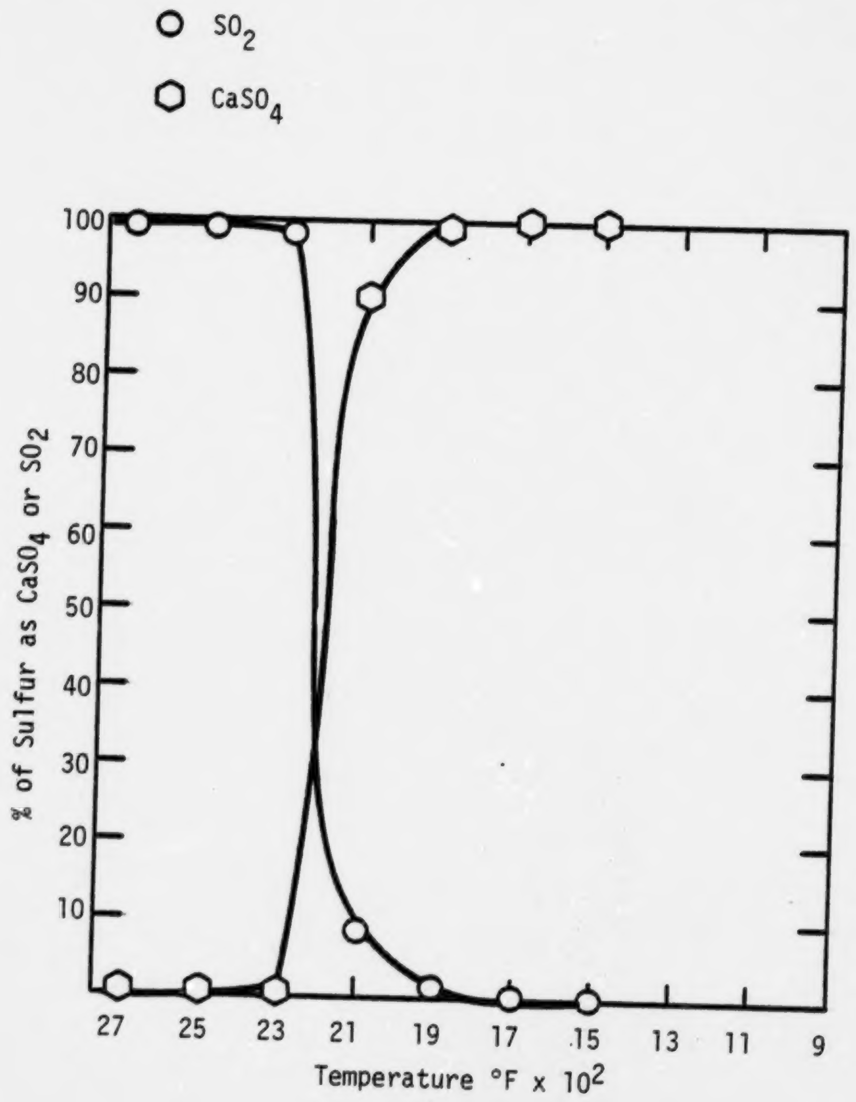


Figure 4-1. Equilibrium sulfur species distribution, fuel lean propane + H_2S + $CaCO_3$, SR = 1.20.

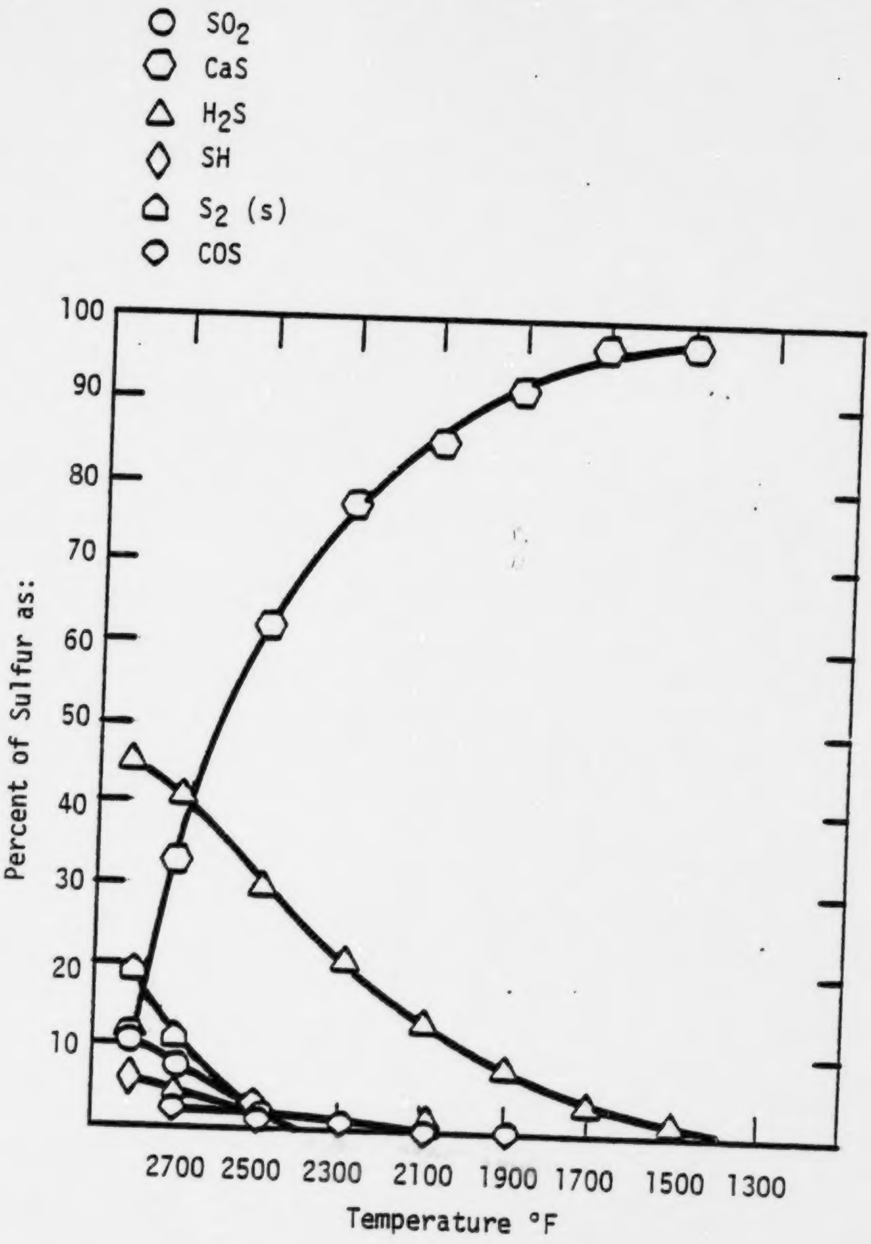


Figure 4-2. Equilibrium Sulfur Species Distribution, Fuel-Rich Propane - H_2S + $CaCO_3$, SR = 0.60.

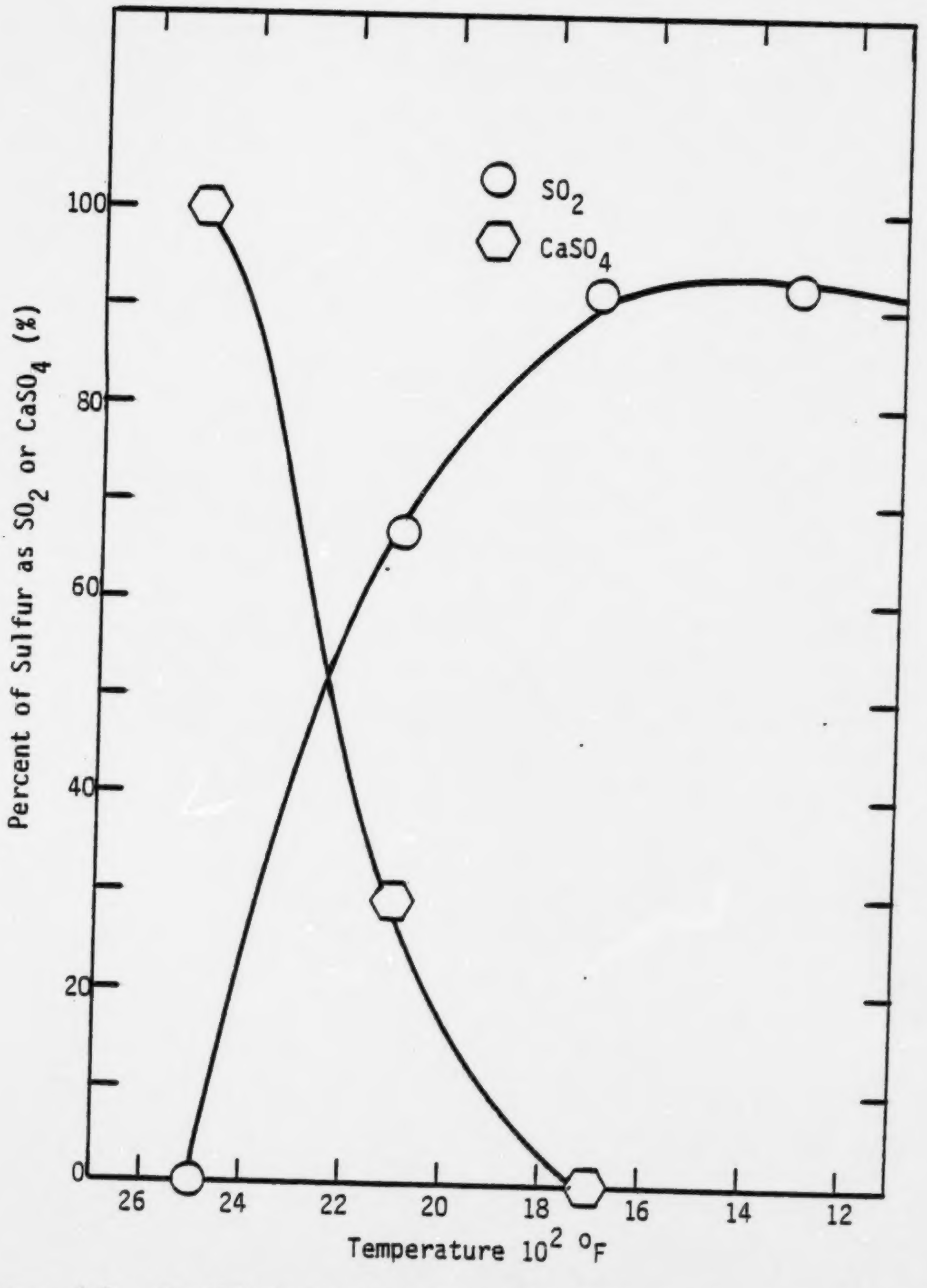


Figure 4-3. Equilibrium Calculations for Fuel Lean Sulfur Species Distribution, Lignite Coal + $CaCO_3$, Ca/S = 1.6, SR = 1.25.

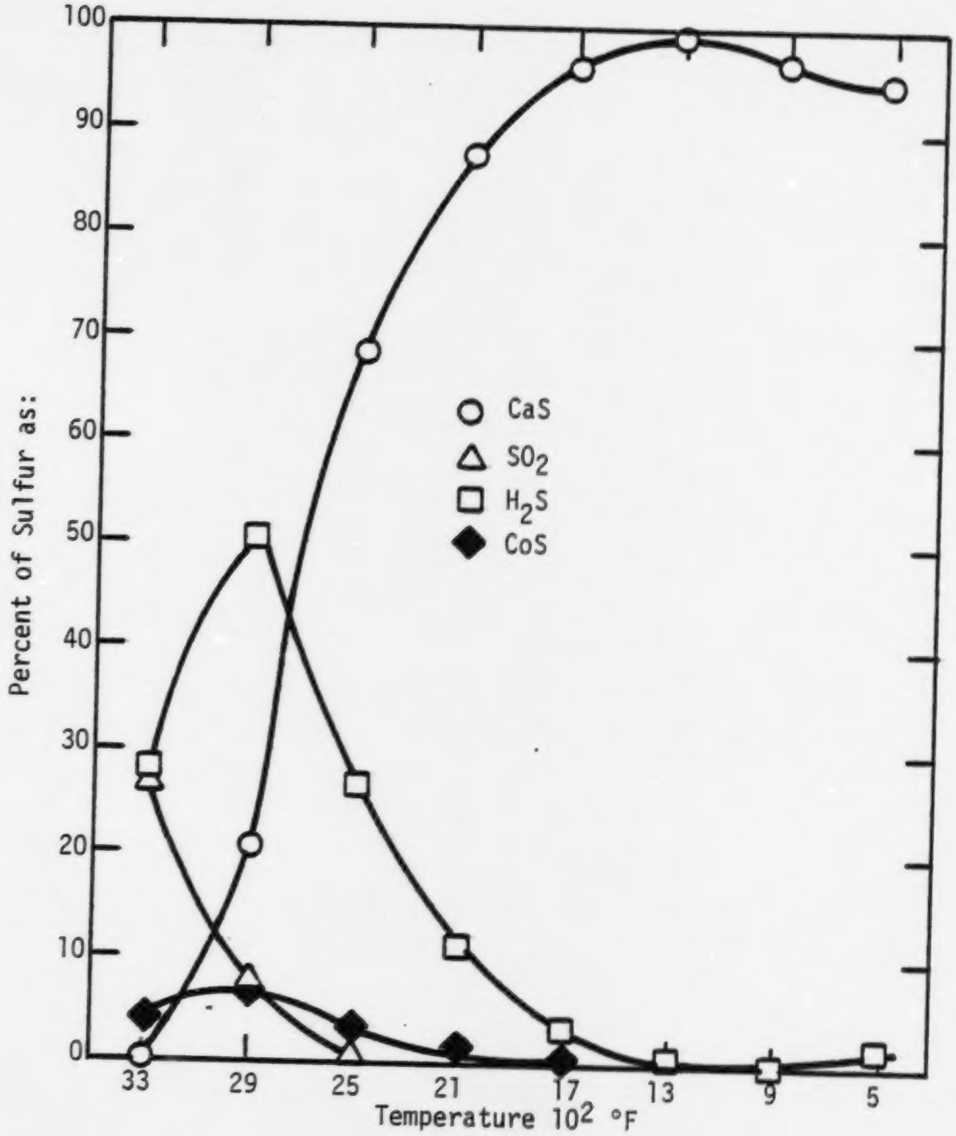


Figure 4-4. Equilibrium calculation for fuel-rich sulfur species distribution, lignite coal SR_1 =.50

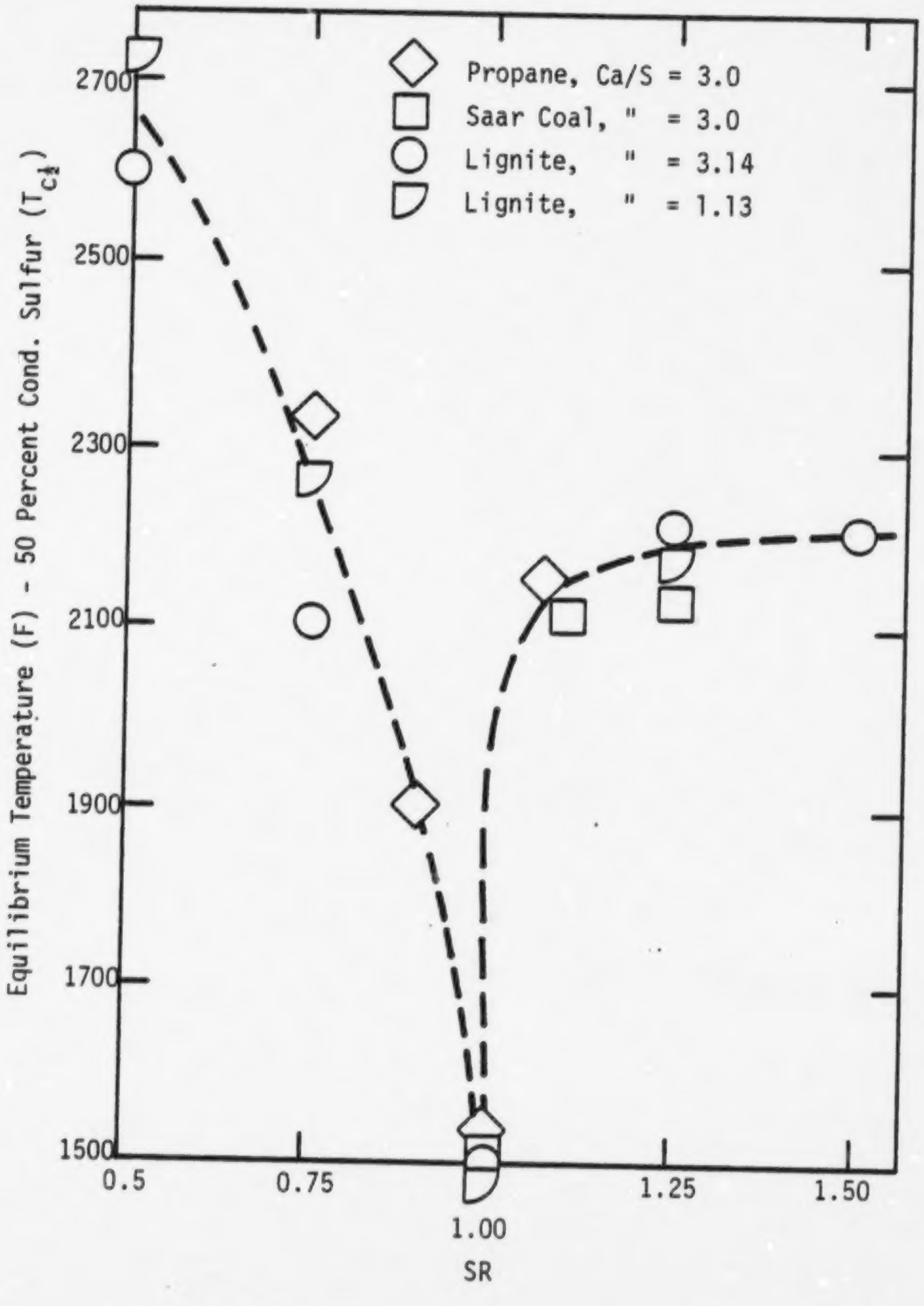


Figure 4-5. Equilibrium temperature for 50 percent condensed sulfur (CaS or $CaSO_4$) as a function of overall fuel/air stoichiometry, SR. Lignite data from (Maloney, et al, 1978).

4.2 Inherent Capture

The natural retention, or inherent capture, of sulfur in coal-fired furnaces has been reported and investigated by several workers, including Brown, et al. (1979), Hein (1981), Gronhovd (1973), Maloney (1978), and others. The inherent capture of sulfur in coal-fired systems is a function of the coal and coal ash composition, the furnace type, and operating conditions, including: mixing, excess air, load, and heat extraction (wall conditions). There are several empirical correlations of inherent sulfur capture with such parameters as ash composition developed by various investigators. One correlation, developed by Gronhovd (1973) for North Dakota lignites, was applied to experimental data obtained in a pilot-scale research boiler, firing lignite coal, at CCRL with good results.

Sulfur emissions for a variety of coals used for bench-scale studies of NO_x formation have been measured as part of the overall combined NO_x/SO_x research program. SO_2 emissions from the coals burned were seldom as great as would be measured for 100 percent conversion of the fuel sulfur. Figure 4-6 shows the sulfur retention (inherent capture) of the various coals as a function of coal sulfur content. There is no direct correlation between fuel sulfur and sulfur retention for the coals burned. An attempt was made to correlate the inherent capture data with the coal ash content, using Gronhovd's correlation. This correlation:

$$\text{Percent of input sulfur emitted} = 110.0 - 12.7 \frac{CaO}{Al_2O_3} - 48.1 \frac{Na_2O}{SiO_2}$$

was applied to the coals used for the bench-scale NO_x studies giving the results shown in Table 4-1. The only coal which exhibited inherent capture similar to that predicted was the Texas lignite.

4.3 Program Definition Experiments: Gas-Fired

In order to: help define the scope of the boiler simulator furnace experiments; to provide data on the sulfur capture process which would help define design criteria for the boiler simulator furnace; to select parameters of interest for study in the BSF; and to develop required expertise in experimental sampling, analytical methods for sulfur species measurements, and

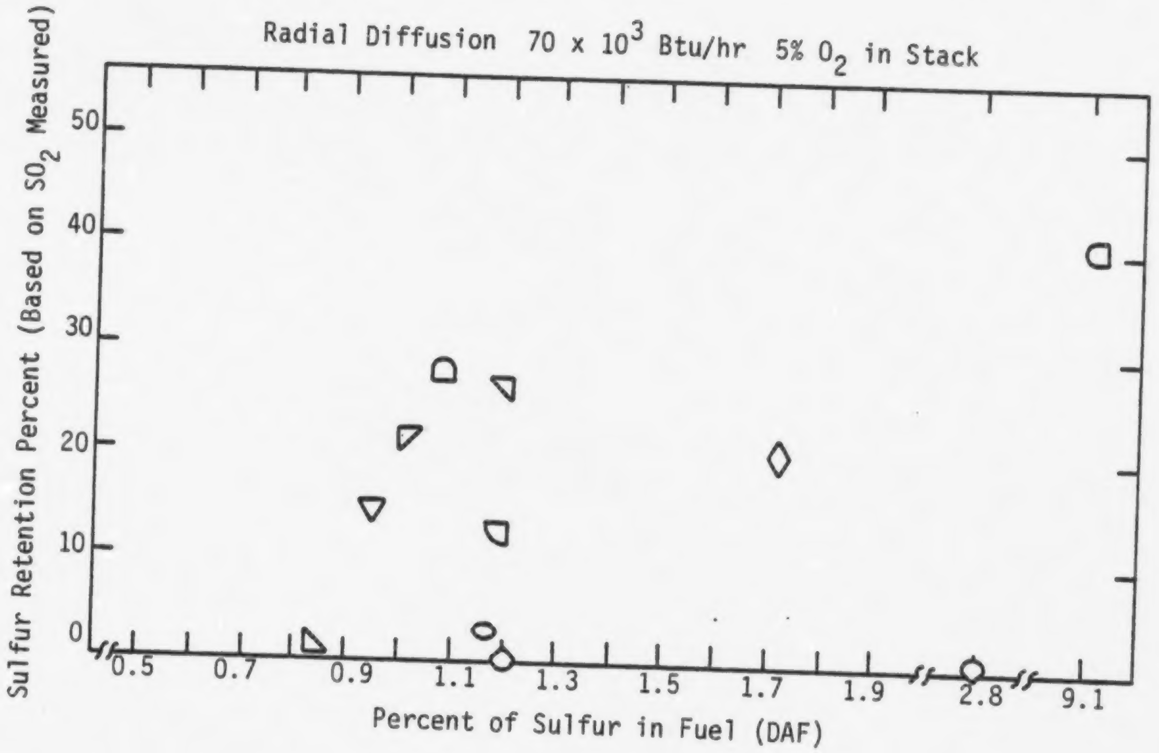


Figure 4-6. Inherent capture as a function of sulfur content.

TABLE 4-1. INHERENT CAPTURE DATA

Coal	Symbol	Percent Capture	Percent Sulfur	Percent Calcium	Predicted Capture
Rosa	⌓	28	1.04		
Hardin	◁	26	1.04		
Farmington	◸	22	1.03	0.66	0
Shell, Texas	◗	12	1.02	1.70	7
Colstrip	▽	14	0.63	0.89	1
Utah II	◺	2	0.76	0.33	0
Gauley Eagle, W.Va.	⬭	3	0.84		
Cadiz, Ohio	ᗡ	41	7.40	0.02	0
Elkay	◇	1	2.47		
German Brown	☒	19	0.51	1.08	9

sulfur capture determinations, a limited set of definition experiments were performed in three small-scale, down-fired, hot, refractory-wall, tunnel furnaces available at the onset of this research program. The facility is described in Appendix B. Sulfur capture in a coal-fired system is a complex process; in order to eliminate some of the complexity (due to variable sulfur evolution and retention characteristics of solid fuels), the first set of experiments were performed in a gas-fired system.

The experiments were designed to give a preliminary assessment of the potential of sorbent injection for sulfur capture and to assess the effects of some combustion parameters on the effectiveness of sorbent injection. Experiments under excess air conditions investigated the general effect of: calcium-to-sulfur mole ratio, sorbent type, furnace load, excess air, and additive sulfur species oxidation state. A brief investigation of capture under physically staged conditions and of solid sulfur species decomposition (CaS and $CaSO_4$) was also performed.

The basic experimental scheme consisted of firing a small, down-fired, hot-refractory-walled furnace with propane/air at 50,000 Btu/hr using a diffusion burner. A sulfur additive, H_2S or SO_2, was metered into the combustion air or the fuel as required by a specific experiment. Solid sorbent was injected into the combustion air at a known rate using air for transport; the sorbent type and feed rate was dictated by the experiment being performed.

The effect of calcium-to-sulfur ratio on sulfur capture using $Ca(OH)_2$ as the sorbent is shown by the data in Figure 4-7. The data was taken over a period of several days and shows reasonable repeatability. Figure 4-8 shows data on the effect of load on sulfur capture for both $Ca(OH)_2$ and $CaCO_3$ sorbents. Two things should be noted: first, the $Ca(OH)_2$ was slightly more effective than the $CaCO_3$; and second, the furnace load had a strong effect on capture for both sorbents. The effect of excess air on sulfur capture using $Ca(OH)_2$ as the sorbent at two loads is shown in Figures 4-9 and 4-10. At low load (30,000 Btu/hr) excess air level had no effect on sulfur capture while at higher load an effect is apparent. The data shown in Figure 4-10 was all taken on the same day. The hysterisis in the capture vs % O_2 curve is probably a thermal effect. The furnace started out hot, at 2% O_2, and was cooled as the excess air was increased to 8% O_2. When the excess air was

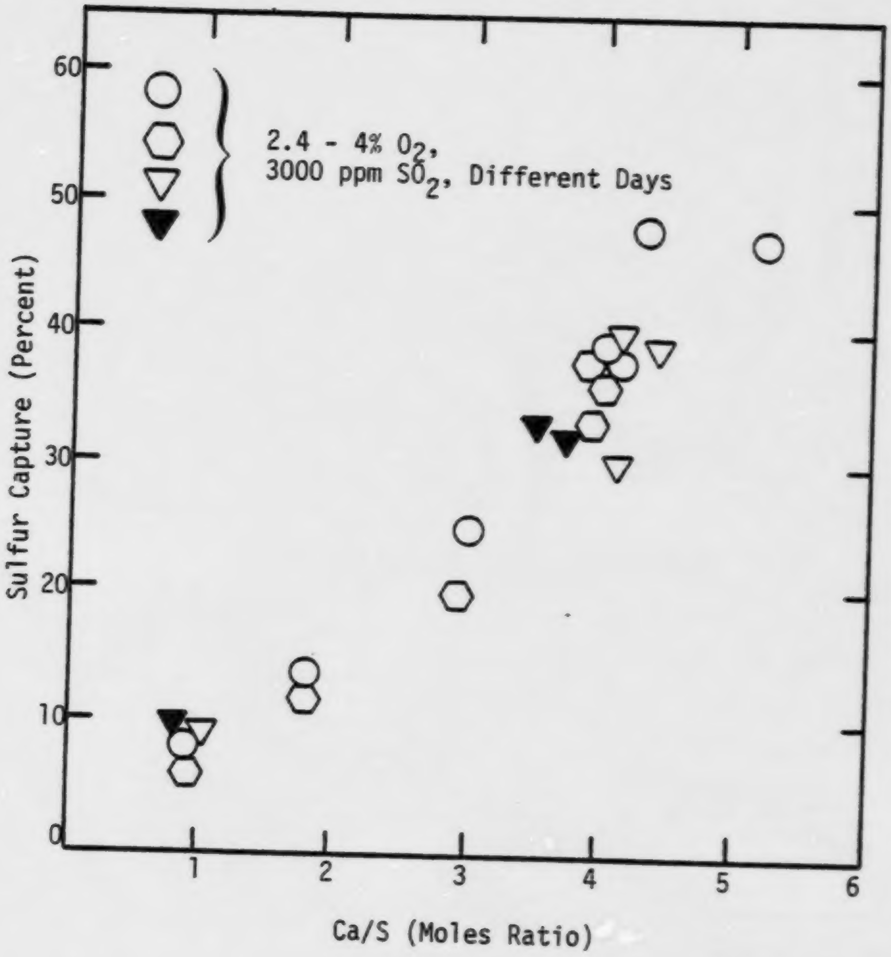
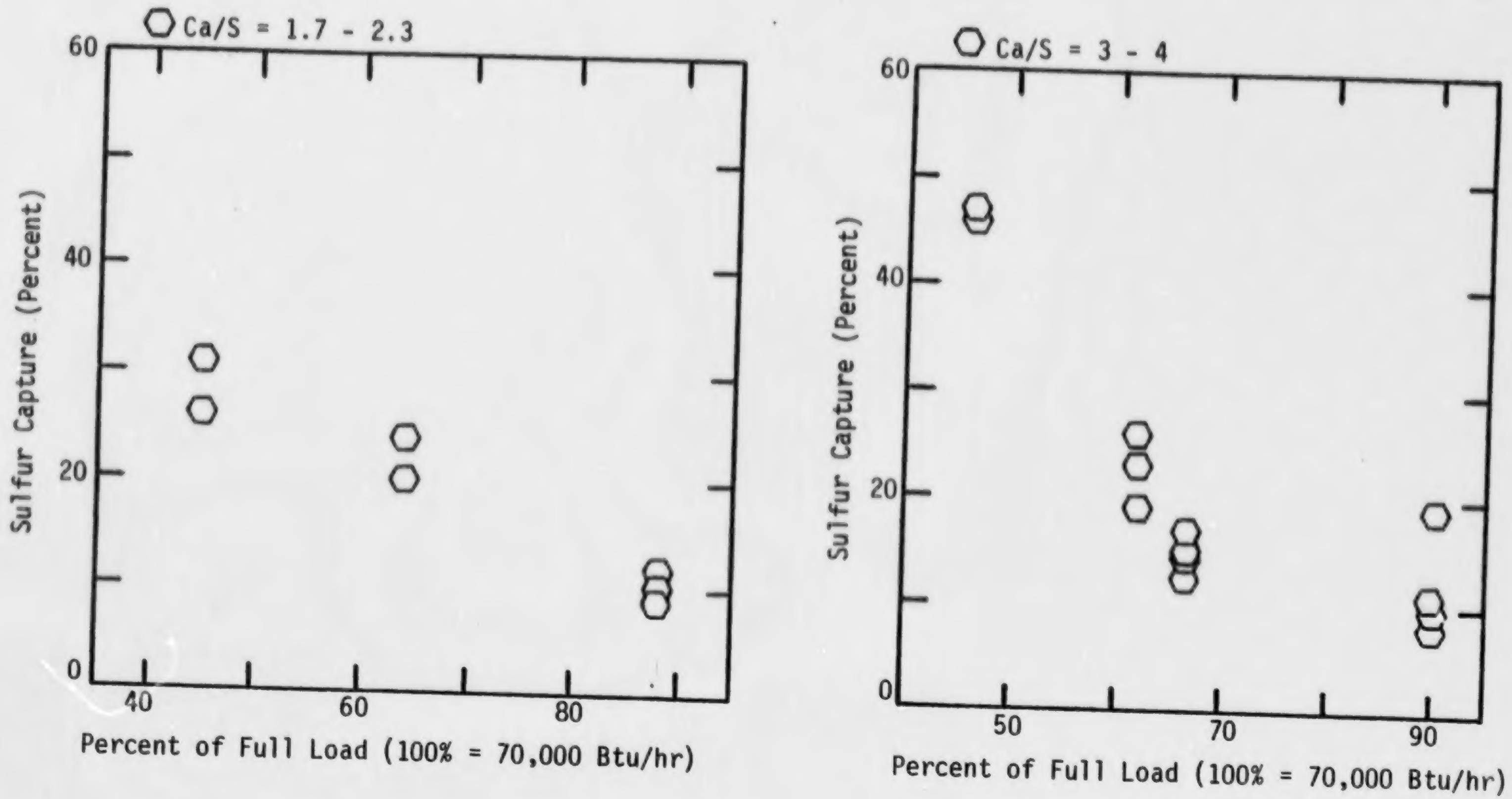


Figure 4-7. Effect of Ca/S on SO_2 capture, 32,000 Btu/hr, repeatability of data.



(a) Ca(CO_3)

(b) $Ca(OH)_2$

Figure 4-8. Effect of furnace load on sulfur capture.

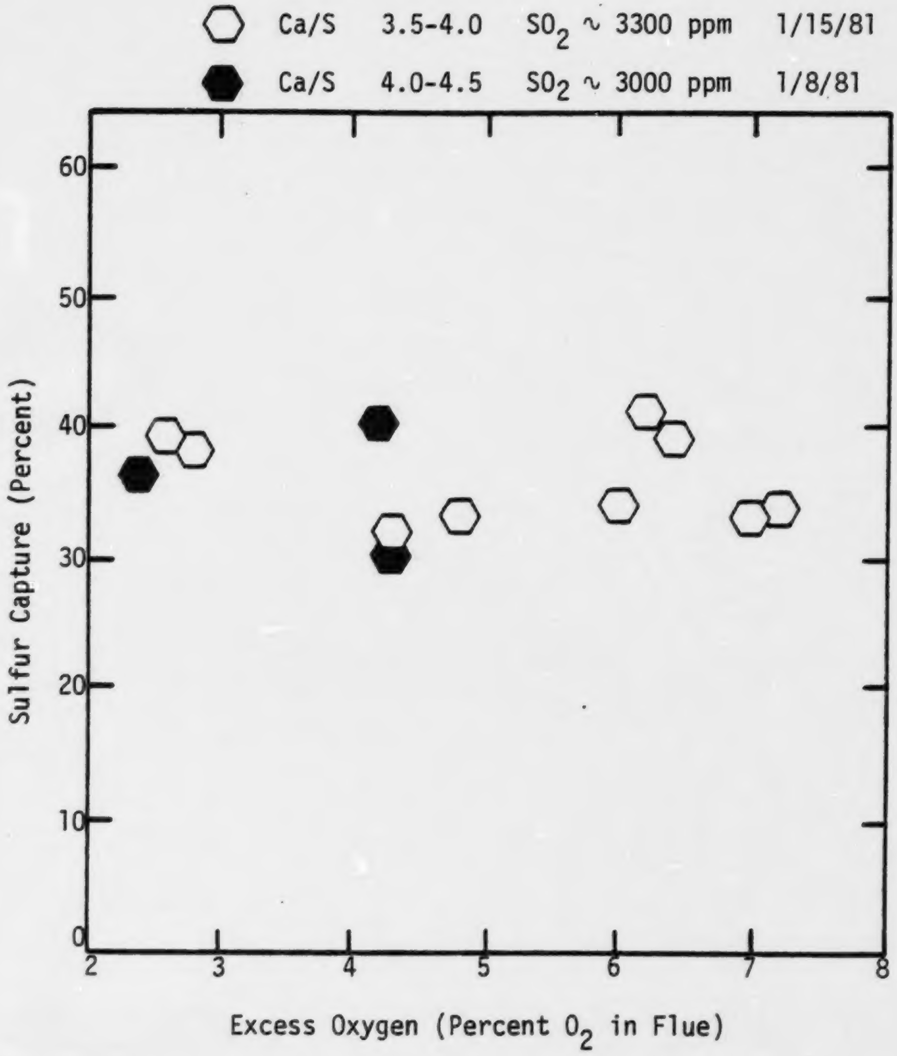


Figure 4-9. Effect of excess air on sulfur capture, 32,000 Btu/hr, $Ca(OH)_2$.

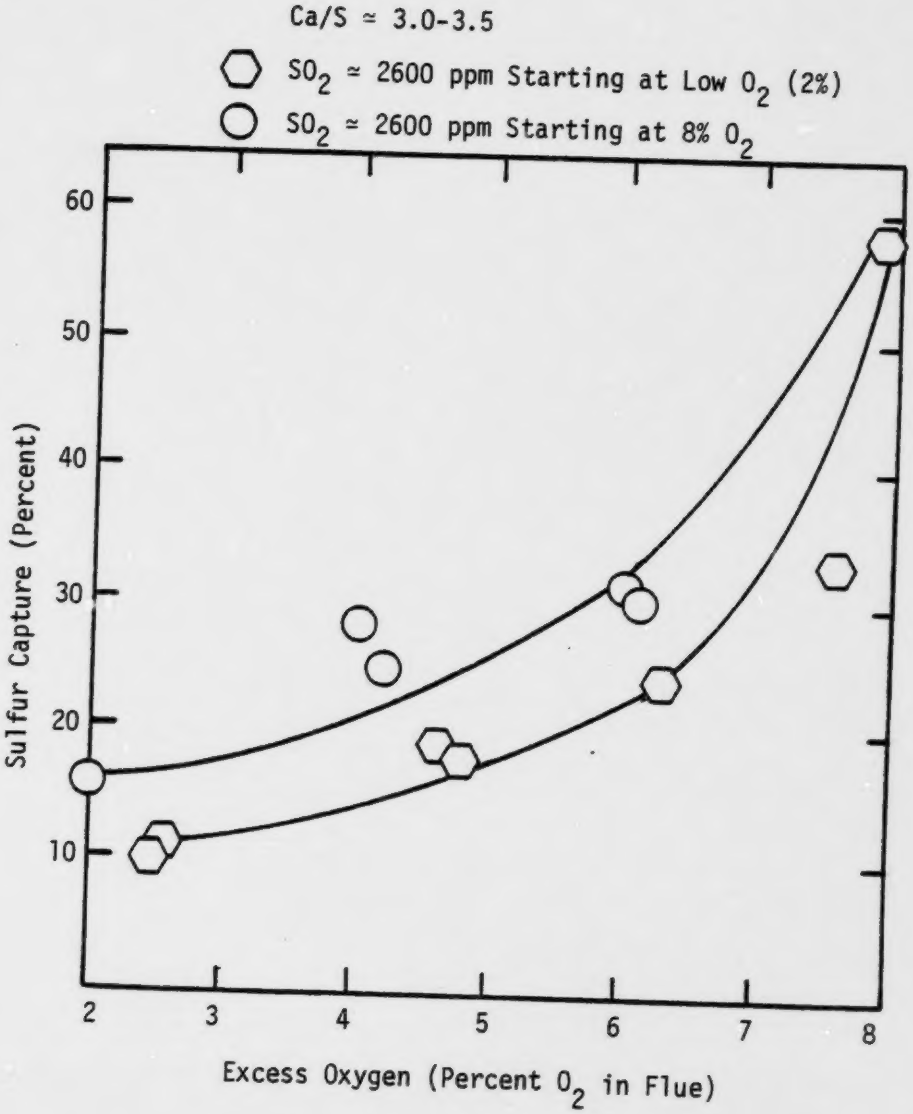


Figure 4-10. Effect of excess air on capture, 48,000 Btu/hr, $Ca(OH)_2$.

increased to 8% O_2. When the excess air was decreased back to 2% to repeat the capture data, a histerisis was apparent. The furnace has considerable thermal inertia and had not returned to the base temperatures at 2% O_2 when the second set of data was taken.

The effect of sulfur species oxidation state on sulfur capture was assessed by adding either H_2S or SO_2 to the combustion air. The data plotted in Figure 4-11 show that, under excess air conditions, the input sulfur species oxidation state has no effect on sulfur capture. The effect of sulfur "location" was also determined. H_2S was added to both the combustion air and to the fuel for several firing conditions. There was no difference in the sulfur capture observed between the fuel additive and the air additive cases.

The effect of fuel sulfur content on sulfur capture was investigated by varying the amount of SO_2 added to the combustion air. Figures 4-12 and 4-13 show curves constructed from data taken at various Ca/S ratios and various SO_2 concentrations but with constant firing rate and constant excess air. The data taken at the low load show a definite effect of SO_2 concentration on capture. The sulfur capture for a given calcium-to-sulfur ratio was higher for higher SO_2 concentration. The data taken at the medium load condition show the same effect but not as strongly.

Results of other work with low NO_x, burners which indicated high sulfur capture in systems with extensive fuel-rich regions, motivated an assessment of the possibility of improved sulfur capture under fuel-rich conditions. The gas-fired tunnel furnace was fired at full load using the diffusion burner with less than theoretical air supplied to the burner and the remainder of the combustion air supplied at a point approximately 45 inches below the burner. The primary (fuel-rich) zone stoichiometry was changed by changing the air flow to the burner. Overall excess air was maintained to give 4% O_2 at the flue. The extent of the staging was assessed by measuring the first-stage CO concentration. Figure 4-14 shows sulfur capture as a function of first-stage stoichiometry (indicated by CO concentration) using $Ca(OH)_2$ added with the primary air. Capture was marginally better than that measured at full load under fuel-lean conditions and was little affected by first-stage stoichiometry.

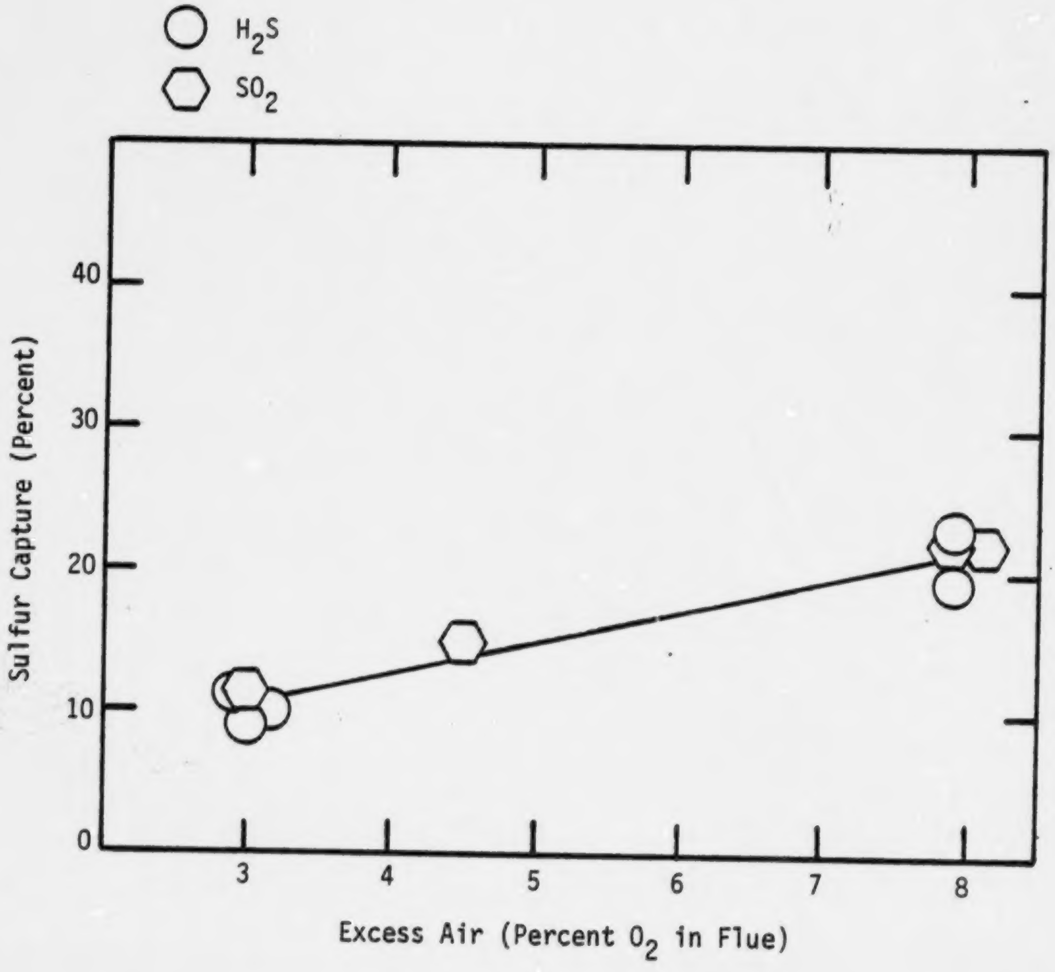


Figure 4-11. Effect of input sulfur on sulfur capture, low load (~30,000 Btu/hr), $CaCO_3/Al_2O_3 \cdot 4SiO_4 \cdot H_2O$ 50/50 mix.

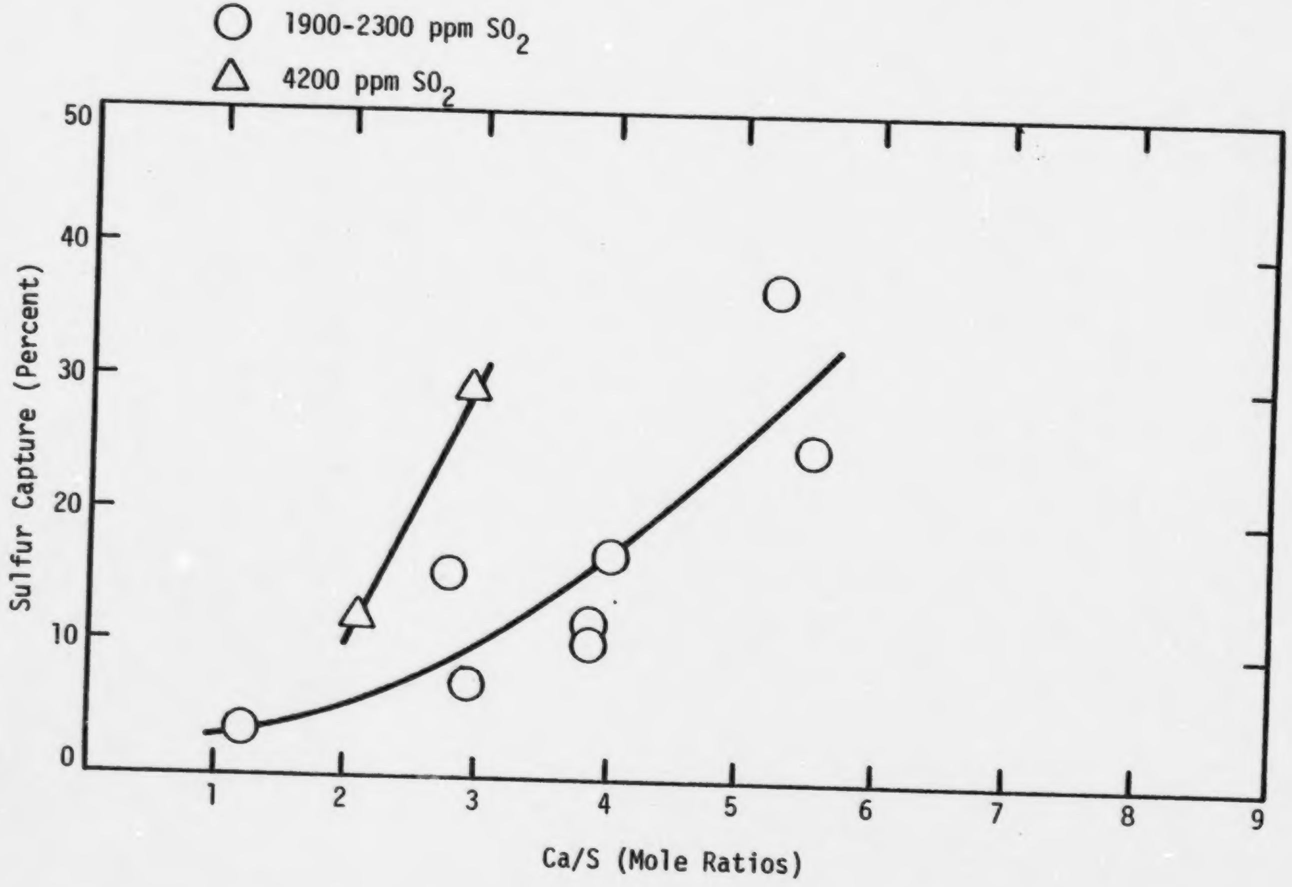


Figure 4-12. Effect of SO_2 concentration on sulfur capture, 4 percent O_2, propane at 32,000 Btu/hr, $Ca(OH)_2$.

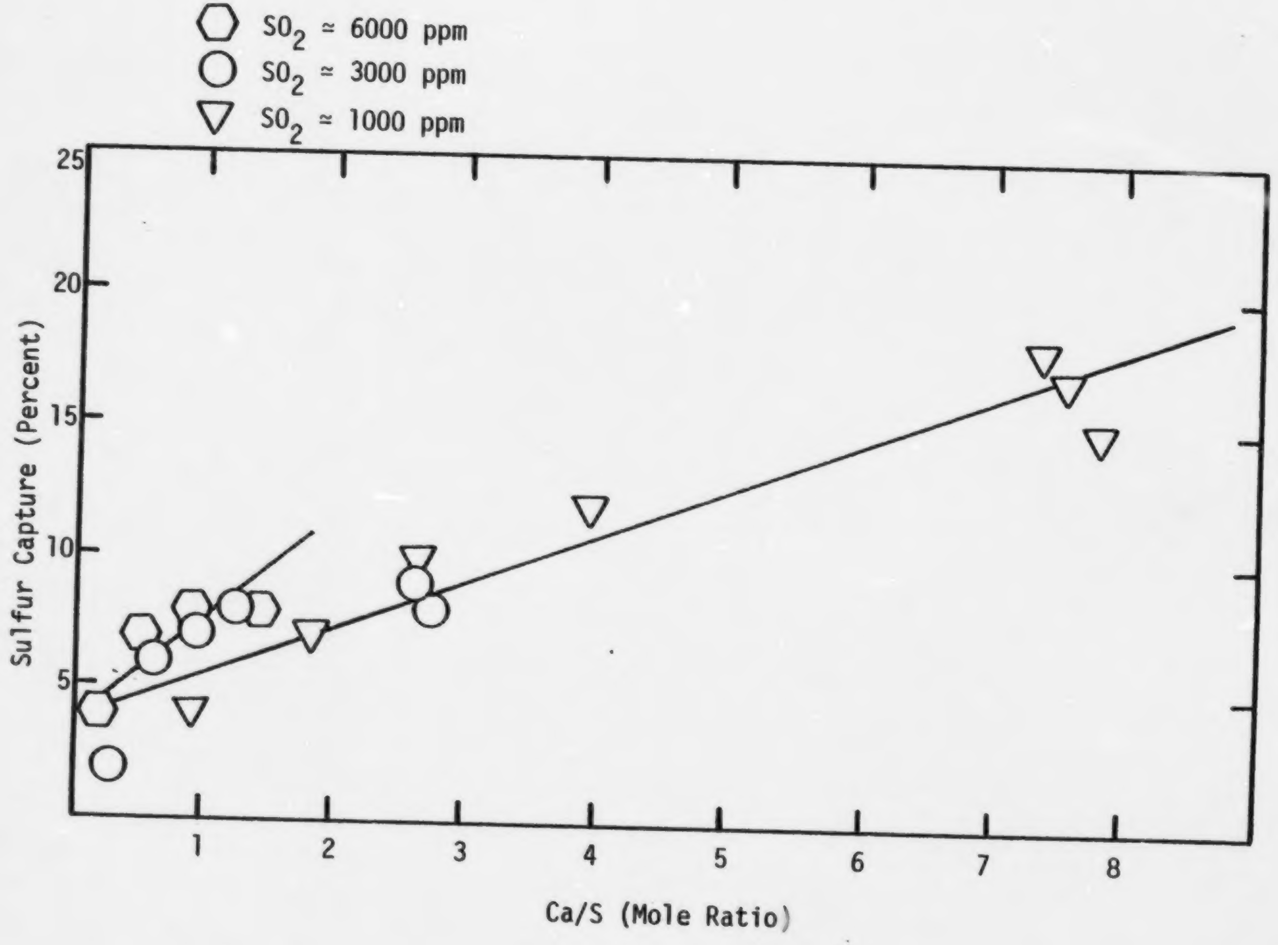


Figure 4-13. Effect of SO_2 concentration on sulfur capture, 4 percent O_2, propane at (48,000 Btu/hr) $Ca(OH)_2/Al_2O_3 \cdot 4SiO_4 \cdot H_2O$, 50/50 mix.

The effect of sorbent addition location on sulfur capture was investigated by adding the sorbent with the second-stage air. The addition of sorbent in the burnout zone, about 45 inches below the burner, gave a slight enhancement of sulfur capture (compare the data in Figure 4-14 with Figure 4-15) even though the residence time of the solids in the furnace was less than half the solids residence time when added with the combustion air.

In addition to the investigation of the potential of sulfur capture by dry sorbents, some investigation into the decomposition of sulfur containing solids was performed. The solids of interest, CaS and $CaSO_4$, are respectively, the expected reaction products from fuel-rich and fuel-lean sorbent/sulfur doped flames.

Calcium sulfate was mixed 50/50 by mass with bentonite (to make it easier to feed) and added to the combustion air at the burner. SO_2 was measured at the furnace flue. The furnace was fired at 50,000 Btu/hr. Solid decomposition was calculated from the solid feed rate and the measured SO_2 concentration. The calcium sulfate did not decompose completely when passed through the furnace. The greatest decomposition observed was 40 percent at 5 percent O_2 in the flue. Excess air rate had some effect on $CaSO_4$ decomposition. As can be seen from the data in Figure 4-16, increased excess air decreased $CaSO_4$ decomposition.

Calcium sulfide was also added to the furnace as a mixture (50/50 by weight) with bentonite. The experimental conditions were similar to those used for the $CaSO_4$ decomposition studies - excess air, 50,000 Btu/hr, solid added at the burner, SO_2 measured at the flue. Excess air level (for the range investigated) had little effect on the decomposition of CaS in the furnace (see Figure 4-17). Combustion air temperature had a slight effect on CaS decomposition (see Figure 4-18), CaS decomposition increased as air preheat temperature increased.

The effect of SO_2 partial pressure on CaS decomposition (at SO_2 levels in the 1000's of ppm range) was investigated by adding SO_2 to the combustion air, pulsing the CaS into the furnace at the burner and measuring the SO_2 concentration change at the flue. The SO_2 increase due to CaS addition

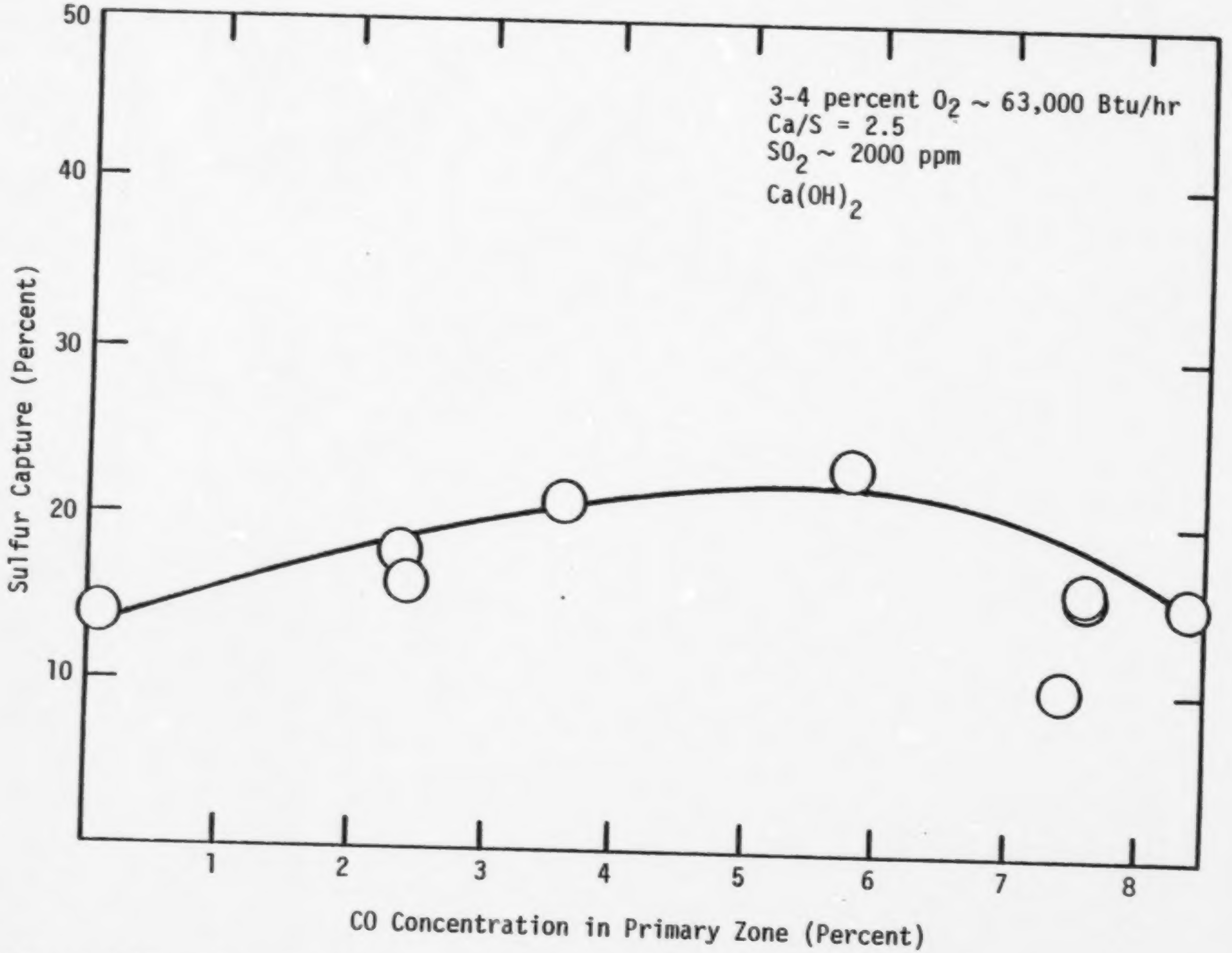


Figure 4-14. Effect of primary zone stoichiometry on sulfur capture, staged combustion, sorbent added with primary air.

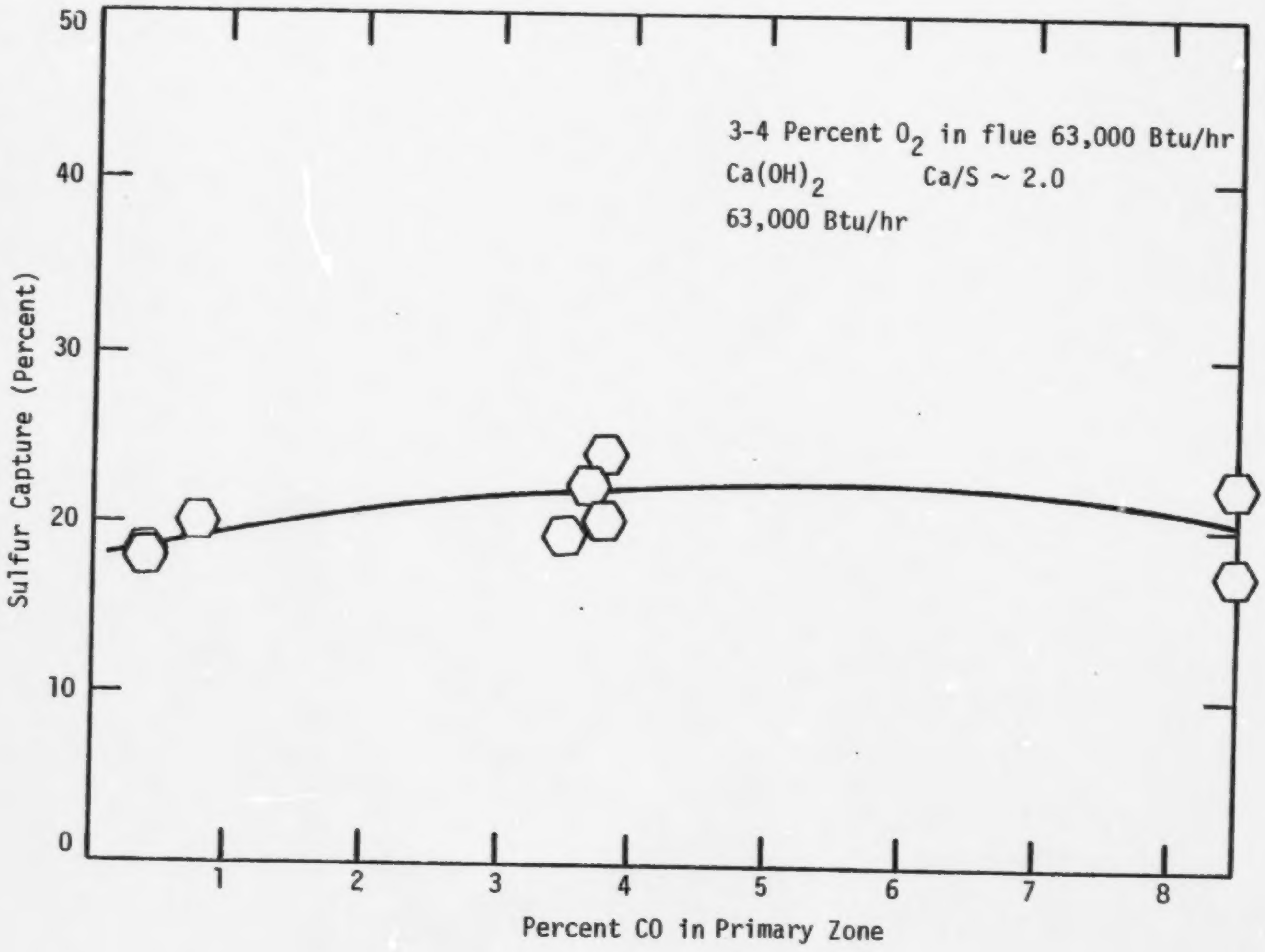


Figure 4-15. Effect of primary zone stoichiometry on sulfur capture, sorbent injected with staging air.

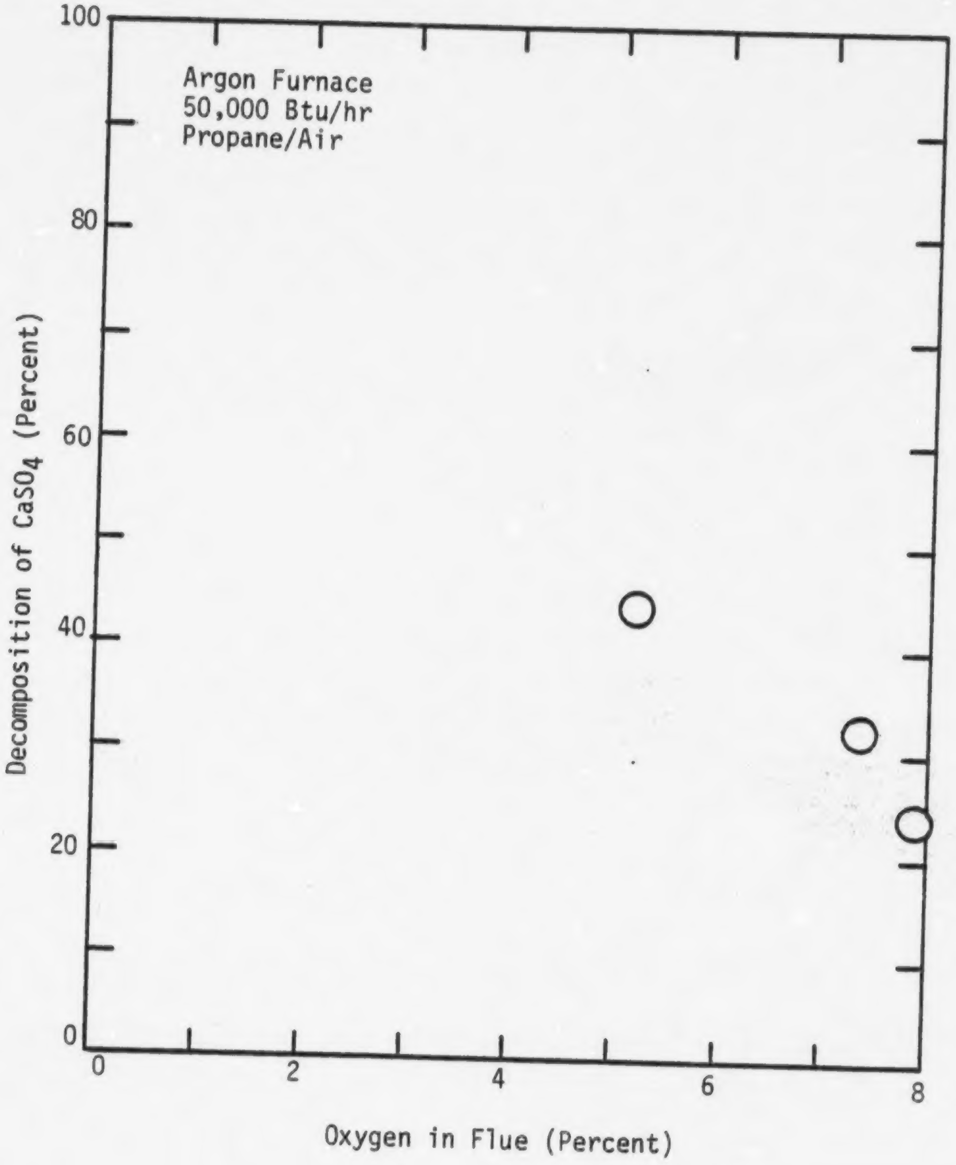


Figure 4-16. Effect of excess air on $CaSO_4$ decomposition.

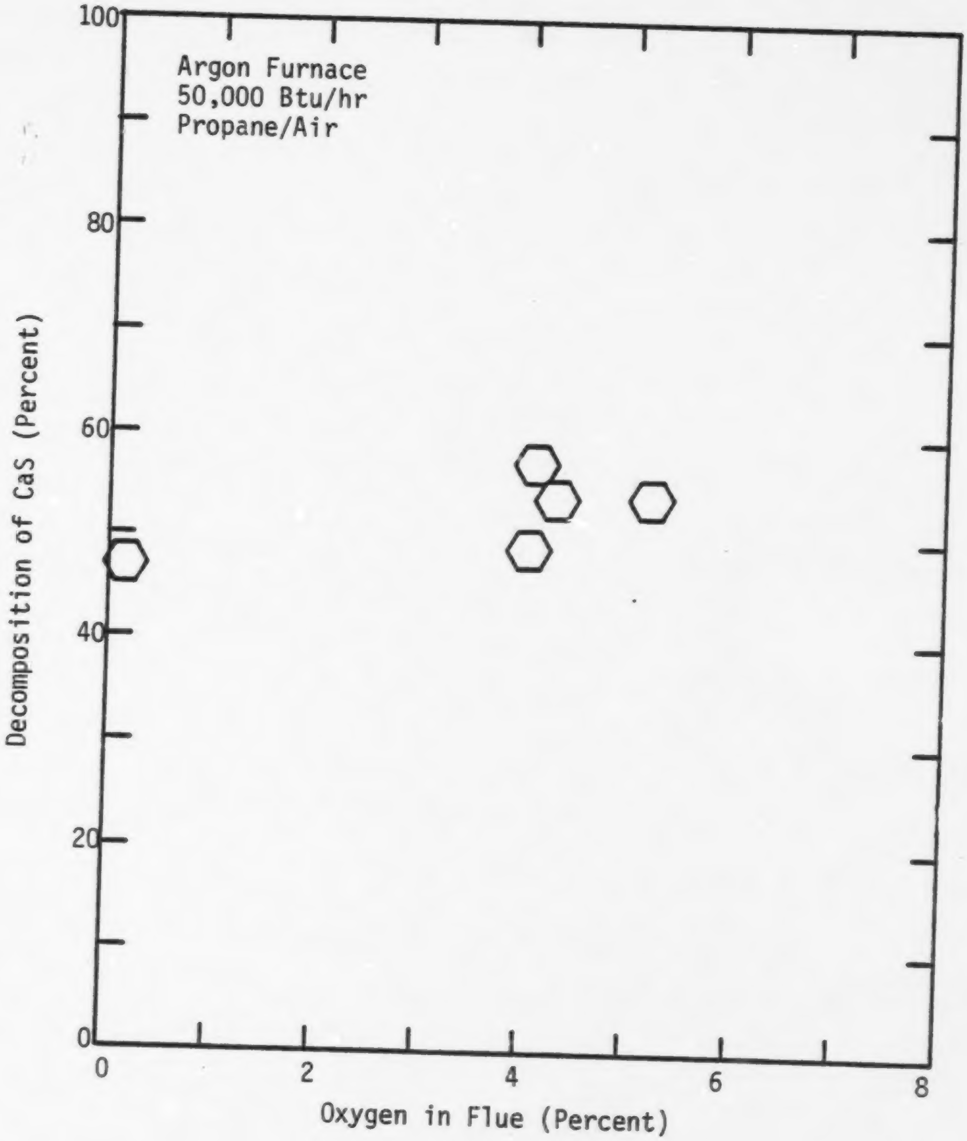


Figure 4-17. Effect of excess air on CaS decomposition.

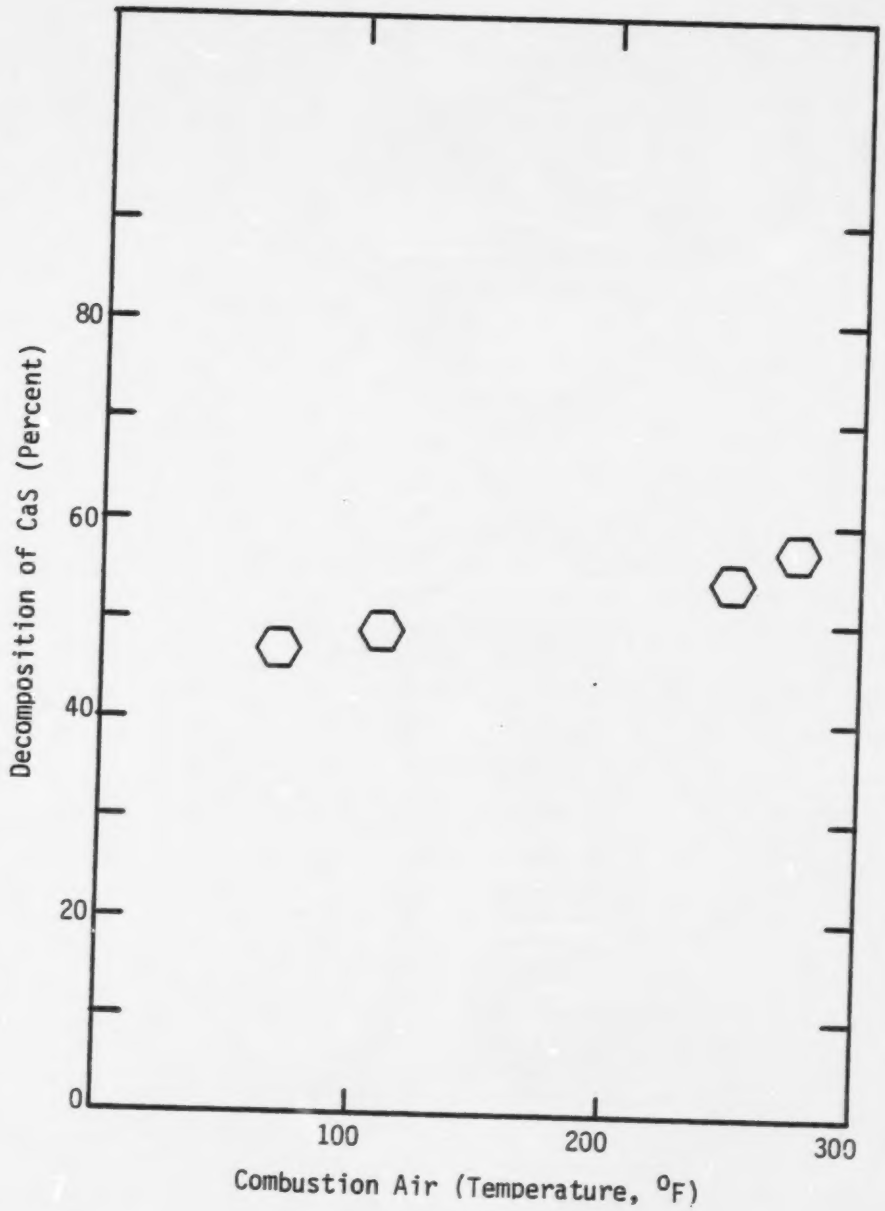


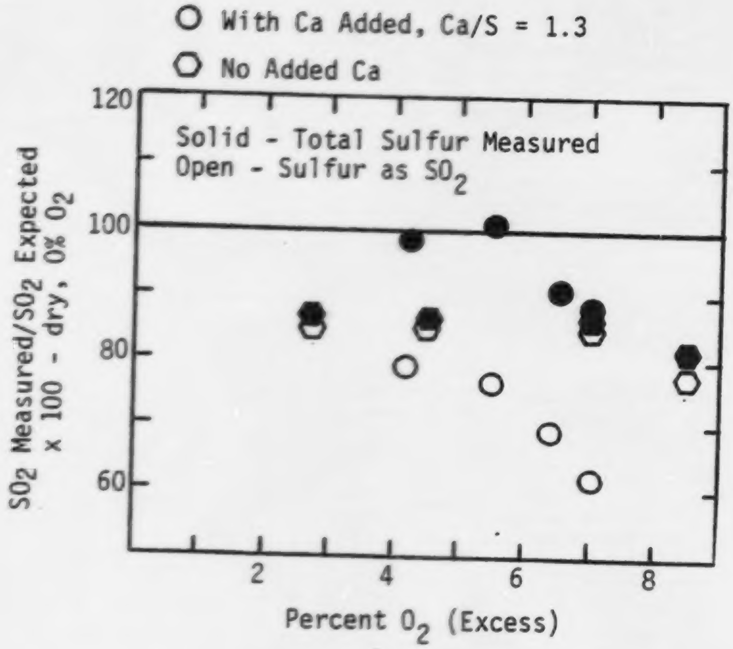
Figure 4-18. Effect of air preheat on CaS decomposition, 50,000 Btu/hr.

was equal to the SO_2 measured for the same CaS feed rate without SO_2 added to the combustion air. This result indicates that SO_2 partial pressure has little effect on CaS decomposition under these conditions.

4.4 Program Definition Experiments: Coal-Fired

A preliminary assessment of the potential of sorbent injection for the capture of sulfur from coal-firing was also performed. The effect of limestone addition on the SO_2 emissions of two coals was investigated. The two coals, Utah 1 and a German brown coal designated KH5, were pulverized with limestone. Both coals were burned in two furnaces (described in Section 7), the Argon furnace and a furnace with a cooled convective section following the radiant section. SO_2 in the flue was measured at various excess air levels and ash samples were taken from the flue of the second furnace after the convective section. The sulfur content of ash samples from the convective furnace was measured. The sulfur content of each coal was measured after pulverization. This measured sulfur concentration was used to predict the SO_2 emissions from combustion by assuming that all the sulfur was converted to SO_2. The expected SO_2 level was 625 ppm for both coals. Figure 4-19 shows a comparison of the SO_2 measured (in the furnace with the convective sections) with the expected SO_2, calculated from the Utah coal sulfur content. The open symbols are for the ratio of SO_2 measured to SO_2 expected, the closed symbols include the sulfur content of the ash (as equivalent SO_2 concentration) in the SO_2-measured to SO_2-expected ratio. Theoretically, the ratio of SO_2 measured, including the ash sulfur content, to SO_2 expected is 1.0; therefore, the closer the ratio to 1.0 the better the sulfur mass balance; sulfur mass balances for conditions where ash samples were taken were acceptable. Comparison of the datain Figure 4-19 for coal with and without added calcium indicates that the added calcium results in a decrease in SO_2 in the gas phase and an increased retention of sulfur in the solid (reflected in a large difference in total S measured and SO_2 measured), especially at high excess air levels.

The data in Figure 4-20 show the ratio of SO_2 measured when firing coal with sorbent added to SO_2 measured when firing coal without sorbent addition as a function of excess air level (or percent O_2 in the flue) for the Argon furnace fired at two loads. (A ratio of SO_2 with Ca/SO_2 without Ca of 1.0 implies no sulfur capture, while a ratio of 0.50 implies fifty percent capture, etc). Both coals gave better sulfur capture at lower loads.



High Firing
Sulfur Balance/Capture
Load: 70,000 Btu/hr
Utah 1 Coal

Figure 4-19. Sulfur balance, convective furnace.

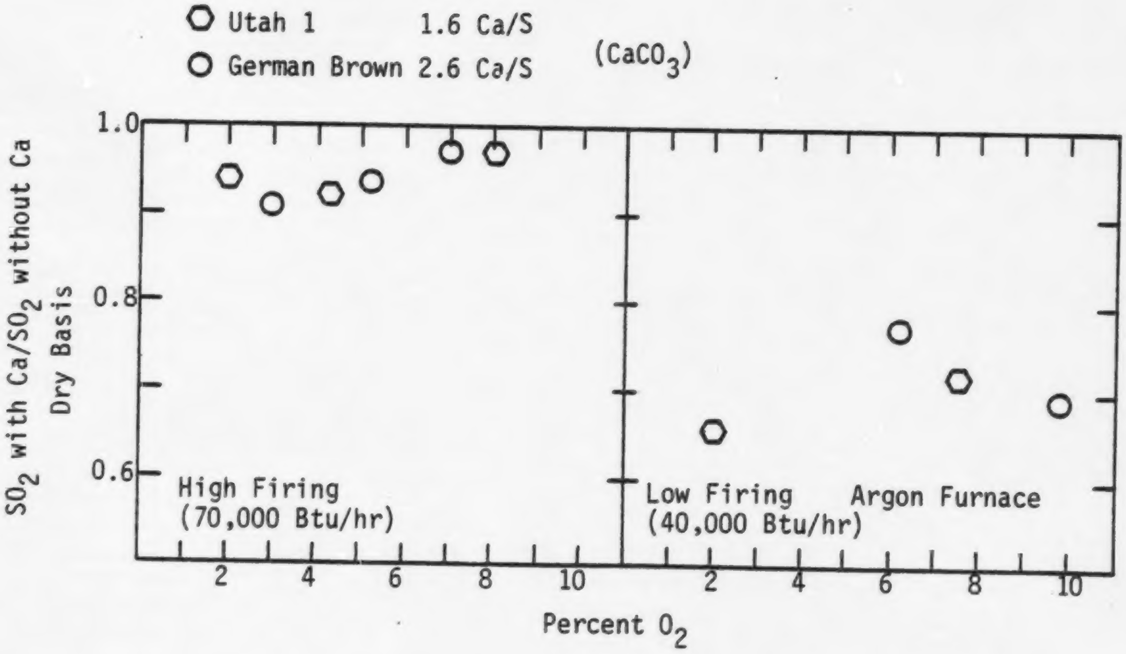


Figure 4-20. Effect of load on sulfur capture.

4.5 Boiler Simulator Furnace Characterization

The Boiler Simulator Furnace (BSF) was a new facility, designed with some unique features (see Appendix B). The furnace and its auxiliary systems were characterized before the parametric screening studies were started. The results of the facility shakedown testing experiments were also used to help select baseline conditions for the sulfur/sorbent interaction studies. Carbon, oxygen, and sulfur mass balances for the furnace were established. Typical furnace temperature profiles for three conditions: two loads uncooled, and with cooling in the radiant furnace at the high load were determined (see Figure 4-21). SO_2 measurement and sulfur retentioned in refractory-walled furnaces are continual sources of experimental difficulty when investigating sulfur capture by dry sorbents. The SO_2 measurement techniques developed and tests of these methods in the BSF are described in Appendix A. The sulfur retention characteristics of the furnace were established. The BSF has three standard sampling locations: at the exit of the radiant furnace, at the exit of the postflame cavity, and at the exit of the convective section. Figure 4-22 shows SO_2 measured at the three sample locations for two SO_2 injection levels on two different days. Figure 4-23 shows SO_2 measured at the three sample points when firing Indiana 2 coal (the shaded area indicates the variation in expected SO_2 due to variation in input sulfur in the coal) for several firing conditions. The SO_2 concentration in furnace decreased 7 to 15 percent, depending on combustion conditions, from the radiant furnace through the convective passages. This sulfur retention may be due to adsorption of SO_2 on the furnace walls and the steel tubes of the convective sections or, in the coal-fired cases, due to changes in retention of sulfur by the ash. The profile of SO_2 through the furnace was one reason for basing sulfur capture calculations on SO_2 measured with and without sorbent rather than on theoretical SO_2 calculated from the fuel sulfur content.

Experiments exploring the effect of load, cooling, fuel injection method (axial vs. divergent) and sorbent location were performed. The results of these preliminary studies were used to establish baseline conditions for the combustion parameter screening studies, discussed in section 5.

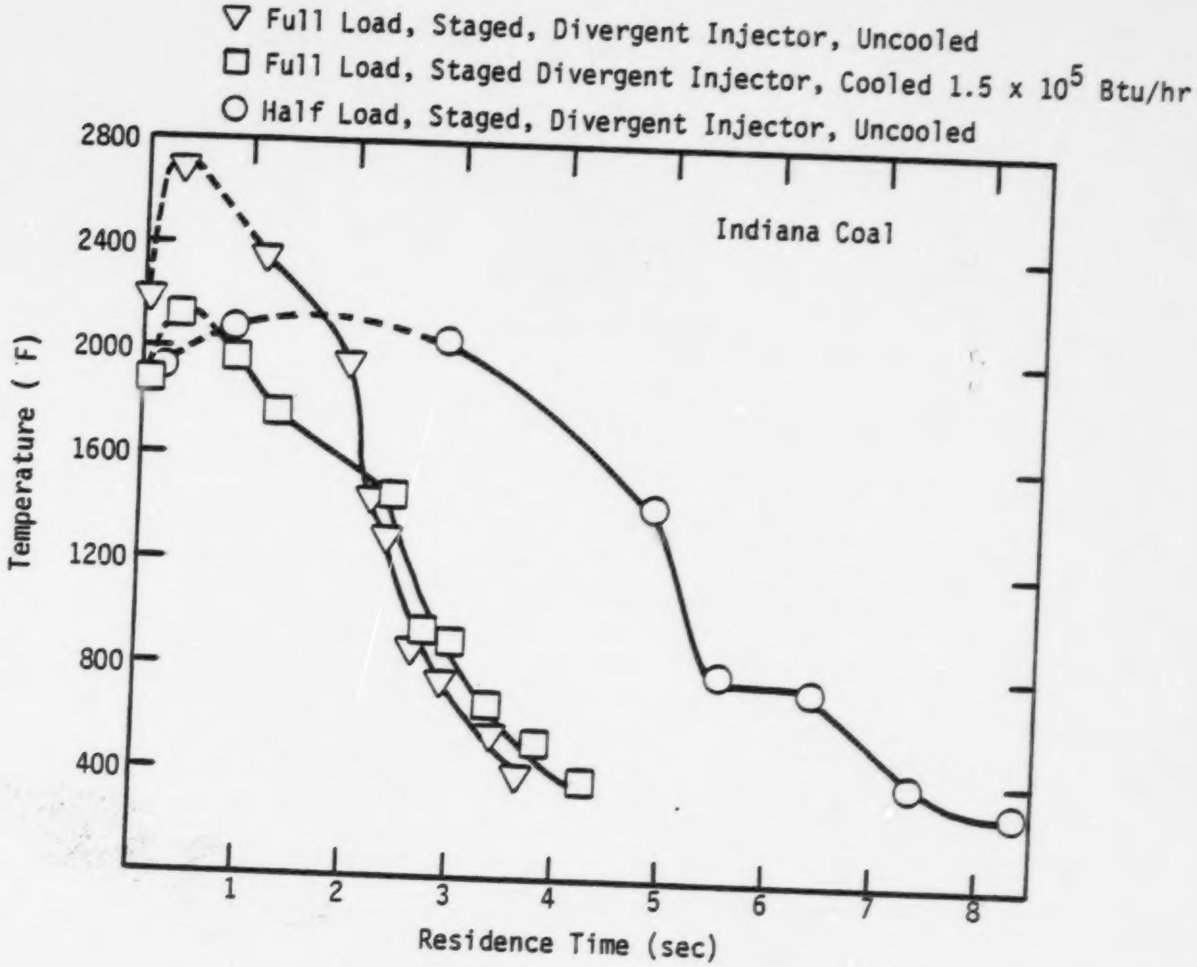


Figure 4-21. Effect of cooling and load on time/temperature profile of BSF.

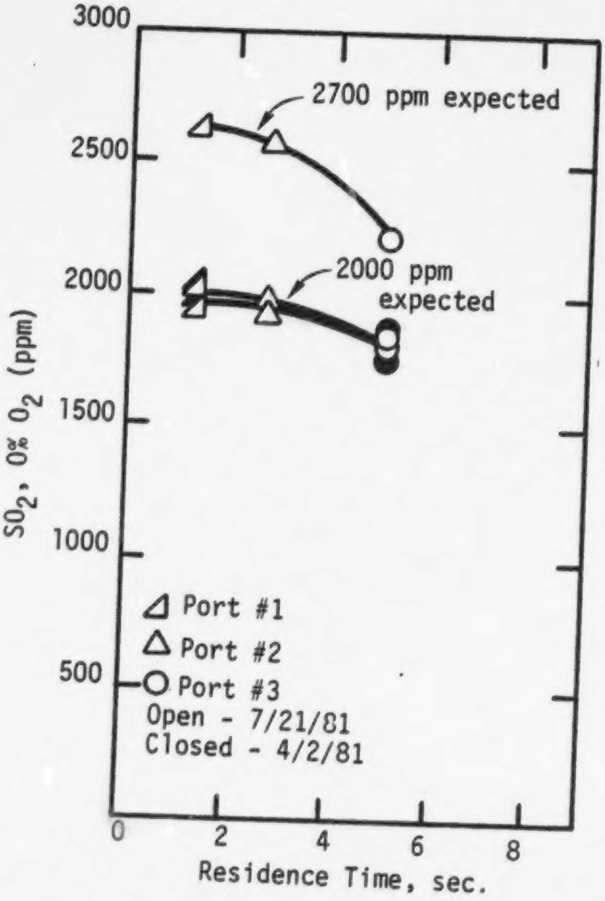


Figure 4-22. Baseline SO$_2$ profile through BSF, propane + SO$_2$ fired.

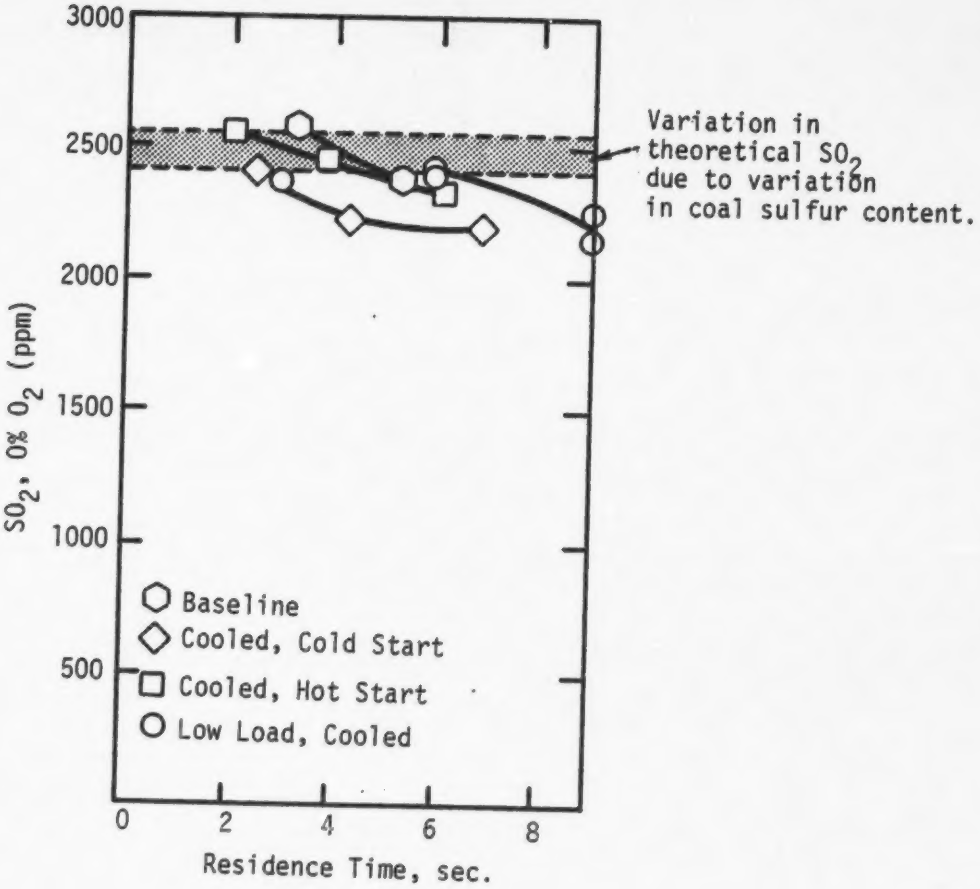


Figure 4-23. Baseline SO_2 profile through BSF, Indiana coal fired.

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Brown, T. D., G. K. Lee, H. A. Bambrough, "Sulfur Neutralization by Lignite Ash: Pilot-Scale Combustion Experiments." Journal of Engineering for Power. An ASME publication, Paper No. 78-WA/FU-7, June 1979.

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Maloney, K. L., P. K. Engel, S. S. Cherry, "Sulfur Retention in Coal Ash." Report to EPA, Contract No. 68-02-1863, EPA 600/7-78-1536, November 1978.

5.0 COMBUSTION PARAMETER SCREENING STUDIES - BOILER SIMULATOR FURNACE (SERIES A)

The first series of experiments discussed in this section, were designed to assess the role of various combustion parameters in the sulfur capture process and to identify parameters and/or experimental conditions for further investigation. Two basic firing modes were used, burner and physically staged.

The BSF was equipped with a sub-scale distributed mixing type burner which had four external tertiary air ports. Burner staging was accomplished in the same manner as in pilot or full scale systems, by injecting a substoichiometric amount of air (generally 60% of theoretical) around the fuel at the burner throat and adding the remainder of the air through the four tertiary air injectors around the burner. Physical staging was accomplished by adding a substoichiometric amount of air through the burner throat and the remainder of the air downstream at the exit of the radiant furnace. The burner staging configuration and standard sample locations are shown in Figure 5-1.

The combustion parameter screening studies were performed in two sets: the first, series A-1, - used the burner staged firing mode and investigated sulfur capture under primarily fuel lean conditions; and the second, series A-2, used the physically staged mode and investigated sulfur capture under fuel rich conditions.

5.1 Results, Burner Staged Studies (A-1)

The effect of various combustion parameters on sulfur capture under predominantly fuel lean conditions was investigated using the boiler simulator furnace fired with Indiana 2 coal. A baseline condition was selected using results of the program definition studies and variations from this base condition were investigated. The baseline firing conditions were:

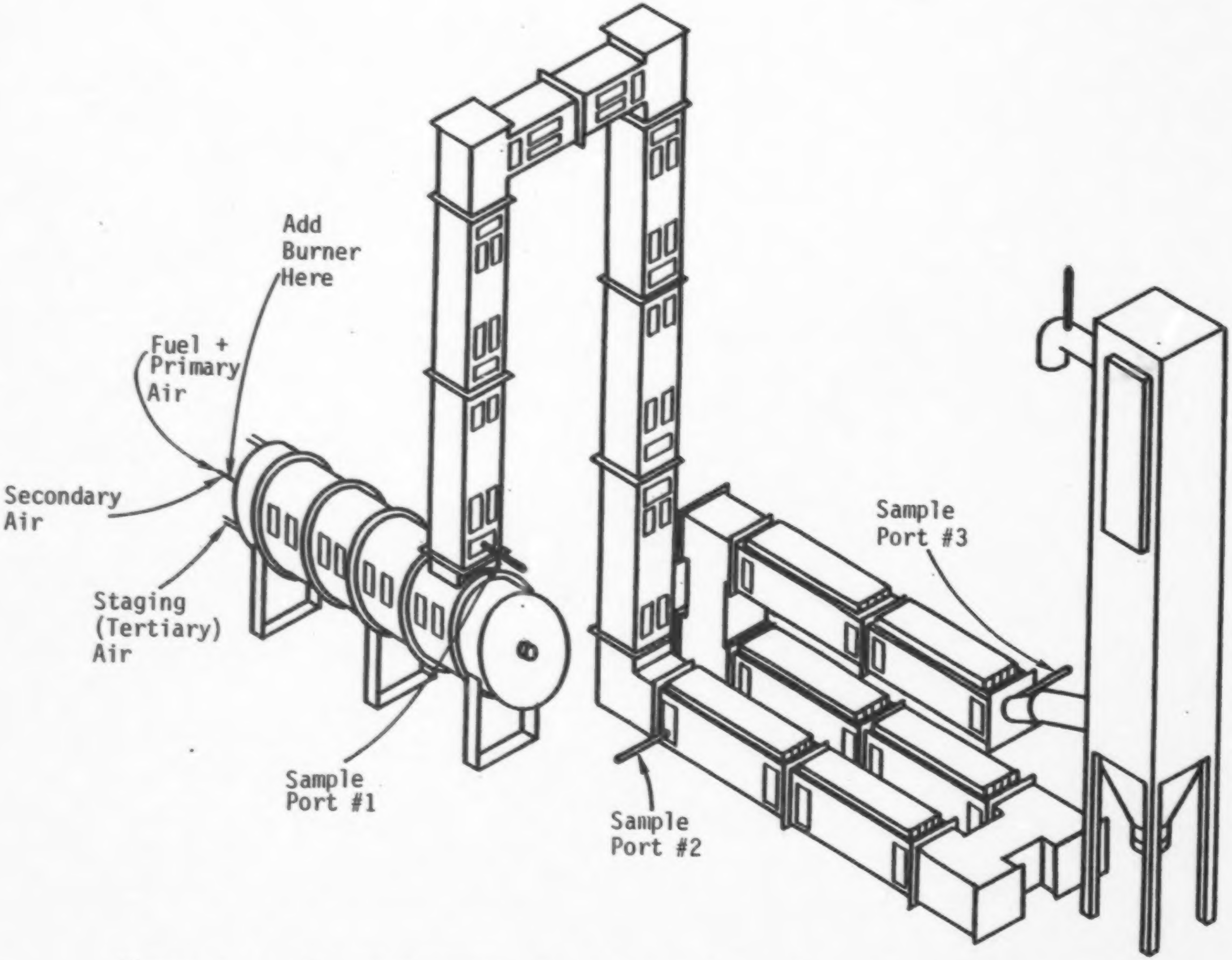

Add
Burner
Here
Fuel +
Primary
Air
Secondary
Air
Staging
(Tertiary)
Air
Sample
Port #1
Sample
Port #2
Sample
Port #3

Figure 5-1. BSF configuration for internal (burner) staging studies.

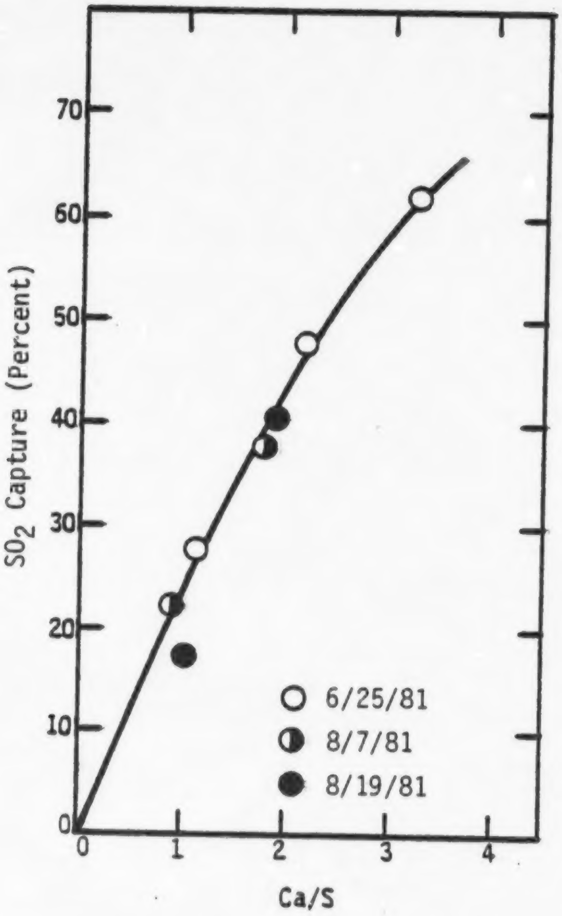
Fuel: Indiana 2 coal (2.4% S)
Sorbent: Vicron 45-3 ($CaCO_3$, 11 μm mean)
Load: 0.8×10^6 Btu/hr
Cooling: 0.1×10^6 Btu/hr in the radiant furnace
Burner: distributed mixing type
Primary stoichiometry (SR_p) : 0.2
Burner zone stoichiometry (SR_b) : 0.6
Overall stoichiometry (SR_t) : 1.20
Tertiary air ports: medium ~ 50 ft/sec injection velocity
Sorbent location: injected with tertiary air (T.A.)

The effect of various combustion parameters on sulfur capture was investigated by changing some of these conditions. Parameters investigated included:

- Firing rate
- Heat extraction rate
- Sorbent location
- Overall excess air
- Burner zone stoichiometry
- Tertiary air velocity

The data shown in Figure 5-2 show the effect of sorbent injection rate on sulfur capture for the baseline conditions. Sulfur capture was based on SO_2 concentration at the exit of the convective section (port 3) measured with and without sorbent injection. The calcium to sulfur mole ratio was based on the coal sulfur content and feed rate and the sorbent mass feed rate. The data shown were taken on three different days, scattered throughout the series A-1 testing, and indicate the good repeatibility obtained. The sulfur capture increased almost linearly with calcium to sulfur ratio, overall sorbent utilization was about 20%.

As indicated in Figure 5-1, there were three standard sample extraction locations, at the exit of the radiant furnace (port 1), at the exit of the postflame cavity (port 2) and at the exit of the convective section (port 3).



Date: As Shown
Rate: 800,000 Btu/hr
Cooling: 100,000 Btu/hr
SR_P: 0.2
SR_B: 0.6
SR_T: 1.2

Coal: Indiana
Ca/S Mole Ratio^2: 2.5
Sample Port: #3
Sorbent: $CaCO_3$, 45-3
Injection Loc.: Tertiary Air

Figure 5-2. Sulfur capture, baseline conditions.

Samples were routinely taken at all three ports during an experiment. The data in Figure 5-3 show sulfur capture through the furnace for the baseline conditions at a calcium-to-sulfur ratio of 1.0. The figure is based on measured captures at three furnace locations and the residence times calculated for these locations. These data indicate that most of the sulfur capture in this case occurred within the radiant zone of the furnace (prior to two seconds residence time). Some capture occurred in the postflame cavity (2-4 seconds). Very little capture occurred in the convective sections (probably due to the low temperatures). The temperatures shown are wall temperatures at the sample point.

To further define the relative effectiveness of sorbent utilization in each combustion zone, all of the axial SO_2 profile data for this condition were converted to relative percentage capture. Relative sorbent utilization in each furnace zone was calculated from the SO_2 capture in each zone (calculated from the difference in concentration at the entrance of the zone and at the exit of the zone) and the calcium-to-sulfur ratio at the entrance of the zone (based on SO_2 at the entrance of the zone and available calcium at the entrance of the zone; calcium used in the previous zone (calculated from the capture in that zone) was assumed to be unavilable). For example, sorbent utilization in the post-flame zone was based on the SO_2 measured at the exit of the radiant furnace with sorbent and SO_2 at the exit of the post-flame zone with sorbent (giving sulfur capture in that zone) and a calcium-to-sulfur ratio calculated for the input (to the burner) calcium-to-sulfur ratio less the calcium used in the radiant zone (calculated from the capture in the radiant zone). Figure 5-4 summarizes these results in terms of the Ca/S ratio for the gases entering each of these sections. These results indicate that, in general, the flame zone utilization is slightly better than that in the post-flame cavity and that the sorbent effectiveness decreases with increasing Ca/S ratio. To further clairfy this effect, these data were replotted allowing for the 0.5 order dependence of the SO_2 concentration driving force (Coutant, et al., 1971). These results are shown in Figure 5-5, and they confirm that the apparent decrease in sorbent effectiveness at high sorbent loadings is largely due to the associated decrease in SO_2 concentration.

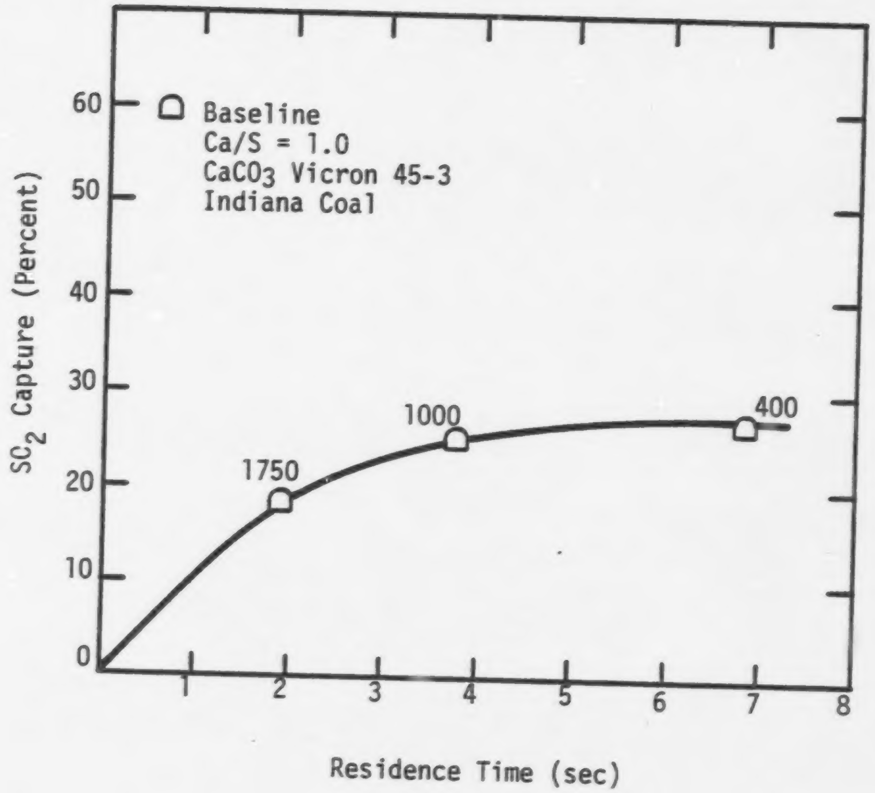


Figure 5-3. Sulfur capture through the furnace, base conditions (as in Figure 5.2).

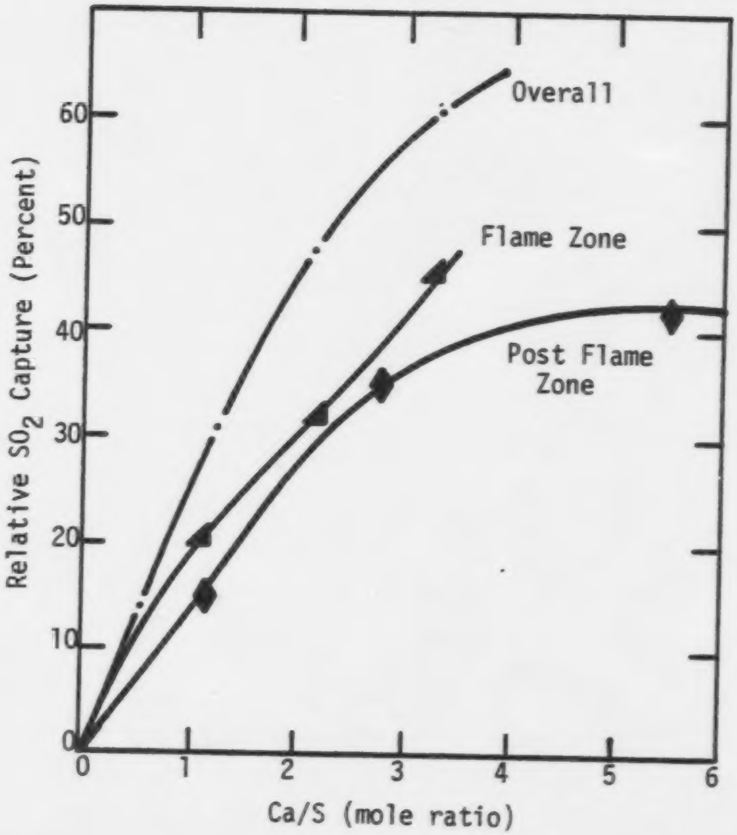


Figure 5-4. Relative SO_2 capture for added $CaCO_3$ and individual furnace sections (conditions as in Figure 5-2).

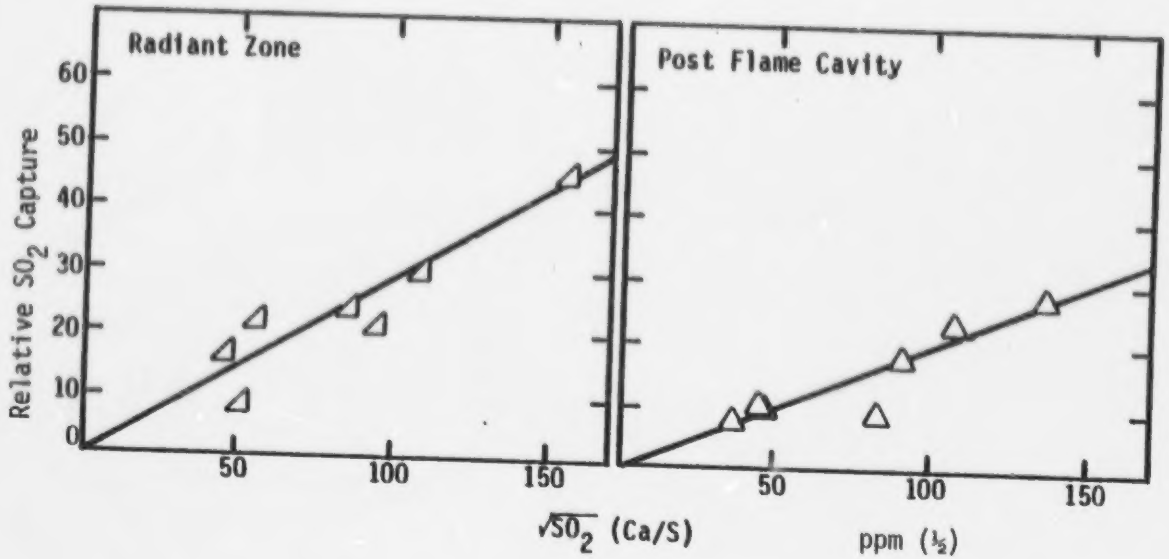


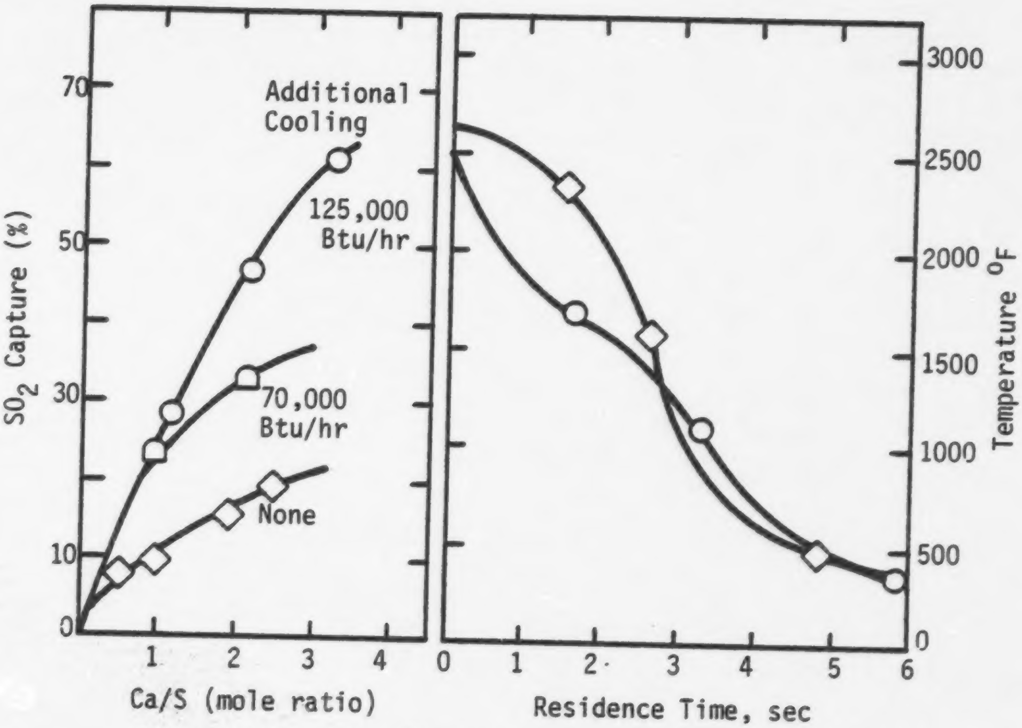
Figure 5-5. Correlation of sulfur capture, baseline conditions, in two furnace zones.

Influence of Heat Extraction Rate

The rate at which heat is extracted from the radiant zone of the system has a dramatic effect on sorbent utilization efficiency throughout the entire combustion process. The radiant zone was cooled with four water-cooled pipes placed along the furnace wall; heat extraction rates were varied by changing heat transfer areas (pipe length in furnace). Figure 5-6 summarizes the data obtained for various cooling levels at the base load condition and shows the effect of cooling on the furnace thermal characteristics. Increasing the radiant zone heat removal by 125,000 Btu/hr (15 percent of the total heat input) resulted in significantly lower temperatures in the first part of the furnace and increased the SO_2 capture almost threefold over the uncooled case.

Figures 5-7 and 5-8 summarize the influence of heat extraction rate at other conditions, including different sorbent locations (milled with the coal and injected into the primary air), low load (580,000 Btu/hr), and changed burner stoichiometry ($SR_B = 0.75$). In all cases, increasing the radiant zone cooling by approximately 100,000 Btu/hr dramatically increased the effectiveness of the limestone sorbent.

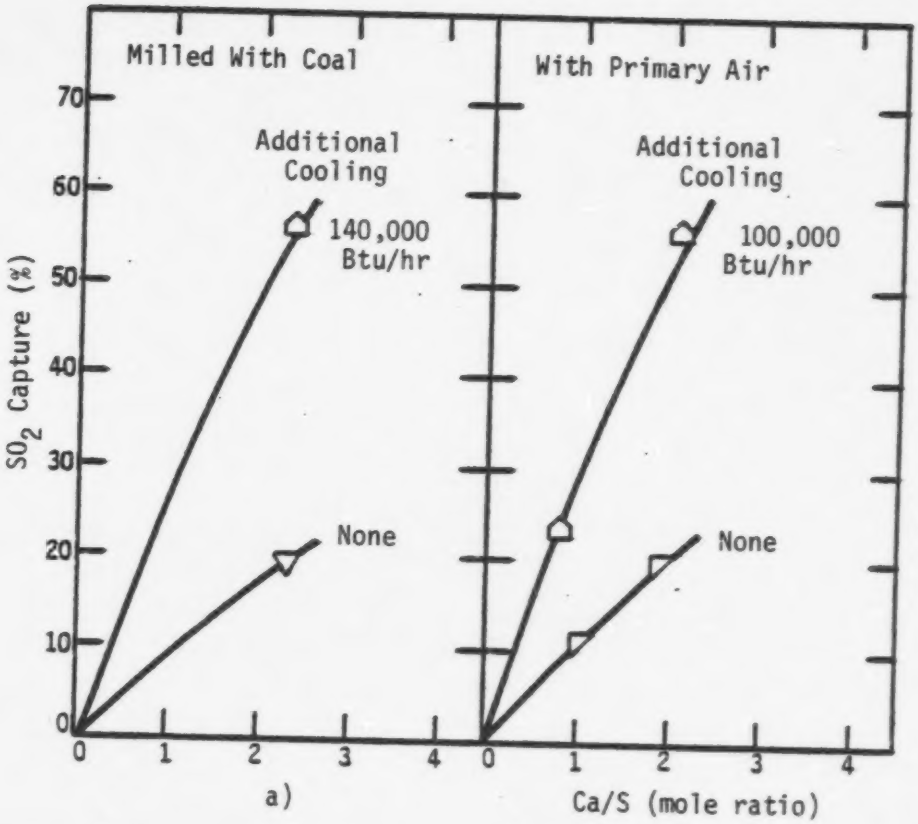
The effect of radiant zone heat extraction on the relative capture in the radiant and postflame zones for two thermal conditions was investigated. Relative capture is plotted against the Ca/S ratio at the entrance of each section (corrected for Ca and SO_2 used in the previous section). The Ca/S ratio was normalized by $\sqrt{SO_2}$ to take account of the driving force effect. It appears that the sorbent material from the uncooled condition is so inactive it is incapable of effectively capturing SO_2 even after the peak temperature zone. Figure 5-10 shows similar results for the low firing rate condition. In this case, cooling had little effect on the capture in the postflame cavity, presumably because neither condition created an inactive sorbent in the flame zone, and because the residence time in the postflame cavity was long enough that a slightly lower bulk-gas temperature (and hence reaction rate) did not significantly decrease relative capture. The data from the radiant zone indicate, again, that cooling significantly increased sulfur capture in the flame zone.



Date: 6/25, 7/1, 7/29/81
Rate: 800,000 Btu/hr
Cooling: As Shown
SR_P: 0.2
SR_B: 0.6
SR_T: 1.20

Coal: Indiana (2.5 percent S)
Ca/S Mole Ratio: As Shown
Sample Port: #3
Sorbent: $CaCO_3$, 45-3
Injection Loc.: Tertiary Air

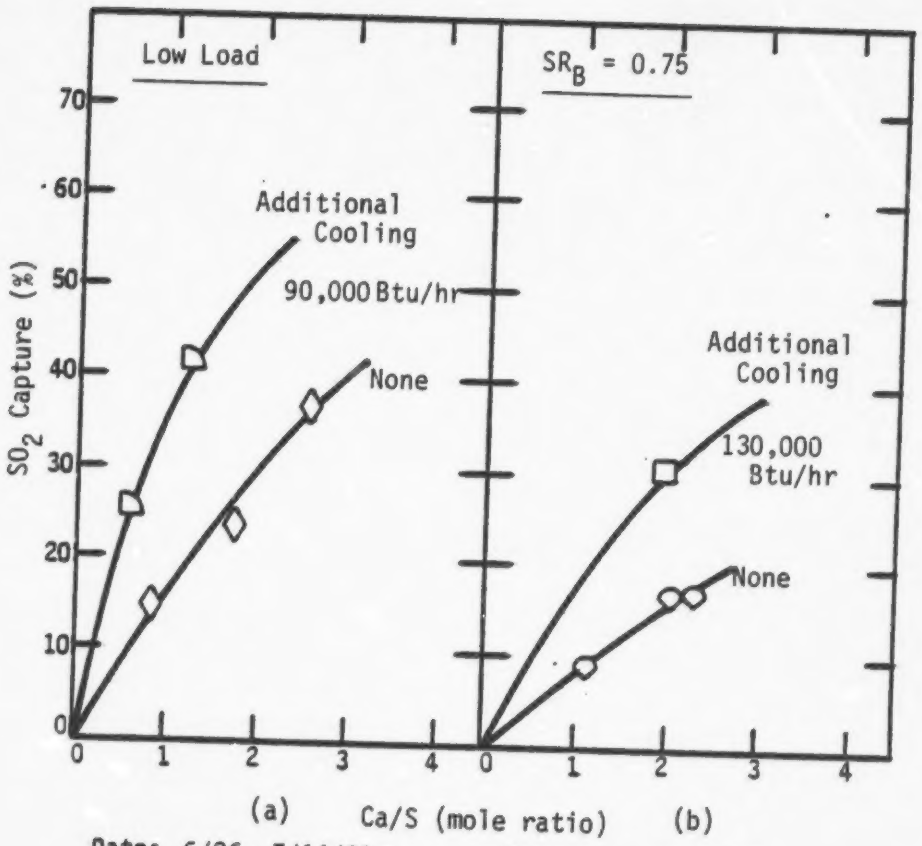
Figure 5-6. Influence of heat extraction rate on sulfur capture and thermal history.



Date: 8/10, 8/21/81
Rate: 860,000 Btu/hr
Cooling: As Shown
SR_P: 0.2
SR_B: 0.6
SR_T: 1.2
Coal: Indiana 2 (2.5%S)
Sorbent: $CaCO_3$, 45-3
Injection Loc.: Milled with coal

Date: 7/29, 8/10/81
Rate: 750,000 Btu/hr
Cooling: As Shown
SR_P: 0.2
SR_B: 0.6
SR_T: 1.2
Coal: Indiana 2 (2.5%S)
Sorbent: $CaCO_3$, 45-3
Injection Loc.: with fuel (primary air)

Figure 5-7. Effect of heat extraction on sulfur capture, sorbent with fuel.



Date: 6/26, 7/14/81
Rate: 580,000 Btu/hr
Cooling: As Shown
SR_P: 0.2
SR_B: 0.6
SR_T: 1.2
Coal: Indiana 2 (2.5%S)
Sorbent: $CaCO_3$, 45-3
Injection Loc.: Tertiary Air

Date: 7/7, 8/6/81
Rate: 800,000 Btu/hr
Cooling: As Shown
SR_P: 0.2
SR_B: 0.75
SR_T: 1.2
Coal: Indiana 2 (2.5%S)
Sorbent: $CaCO_3$, 45-3
Injection Loc.: Tertiary Air

Figure 5-8. Effect of heat extraction on sulfur capture, sorbent with tertiary air.

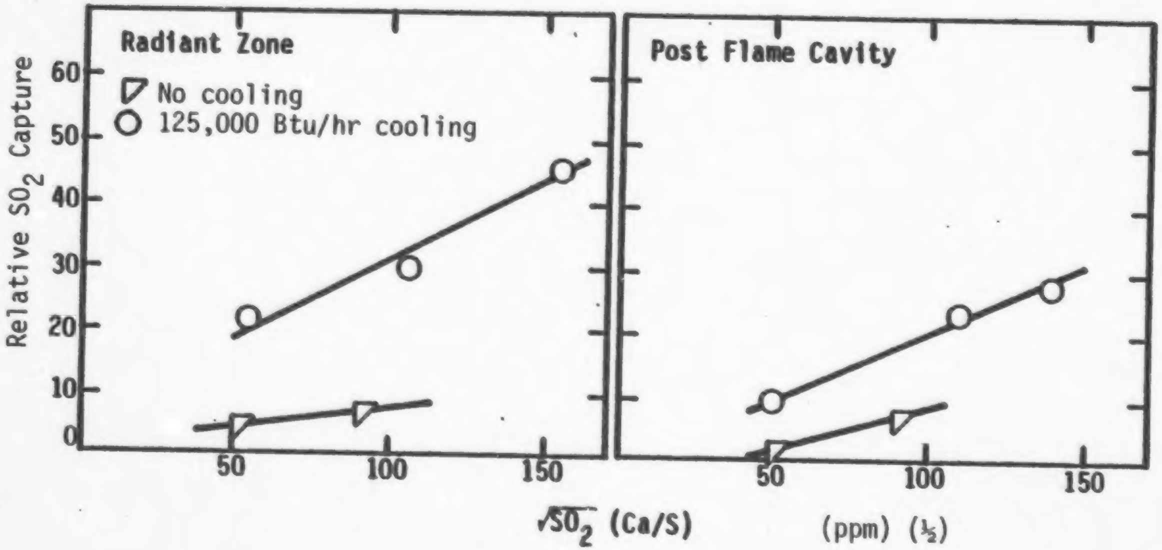


Figure 5-9. Effect of heat extraction on zone capture (conditions as in Figure 5-6, full load with and without cooling).

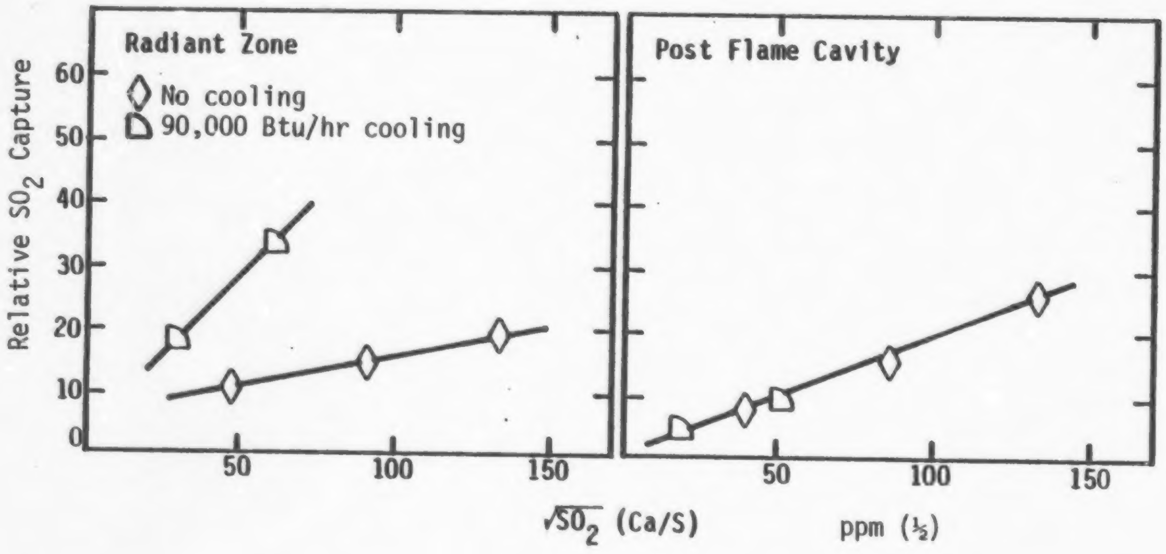


Figure 5-10. Effect of heat extraction on zone capture - low load (same conditions as Figure 5-8, low load with and without cooling).

Influence of Burner Zone Stoichiometry

Figure 5-11 shows data for SO_2 capture after Ports 2 and 3 (postflame cavity and convective section) for a range of burner zone stoichiometries. These data were all obtained without additional cooling in the radiant zone. The burner zone stoichiometry was changed by changing the tertiary/secondary air split. Burner zone stoichiometry was increased by decreasing the tertiary air flow and increasing the secondary air flow; this resulted in an automatic decrease in the tertiary air injection velocity (and therefore sorbent injection velocity) when the burner zone stoichiometry was increased.

The influence of burner zone stoichiometry for both the cooled and uncooled conditions was assessed (Figure 5-12). In general, there was a significant decrease in percentage capture above an SR_B of 1.0. This may be due to the very low tertiary air velocity associated with the excess air case. Figure 5-13 summarizes the effect of varying burner zone stoichiometry on the local capture in each of the major zones for the cooled conditions (as in Figure 5-12b). This indicates that at the excess air condition the sorbent is not reactive in either the flame zone or the postflame cavity.

Influence of Sorbent Location

Figures 5-14 and 5-15 summarize data showing the influence of the sorbent injection location on sulfur capture. In these tests, the limestone was injected with the tertiary air, with the coal and primary air, or premixed with the coal before pulverization. The data shown in Figure 5-14 indicate that under full load and low load conditions (both cooled) the sorbent injection location has essentially no effect on the sulfur capture. Figure 5-15a shows similar data for a sequence of uncooled tests and, as noted before, the overall capture is significantly reduced, but there appears to be little effect of injection mode. Figure 5-15b shows an exception to this general trend. The burner zone stoichiometry was increased to give 10 percent excess air (SR_B = 1.1). In this case, introducing the limestone on the furnace axis with the coal produced significantly better capture than introducing it at a very low velocity through the tertiary air ports.

Influence of Firing Rate

Reducing the firing rate at the base case (cooled) conditions from approximately 800,000 Btu/hr to 570,000 Btu/hr increased sulfur capture

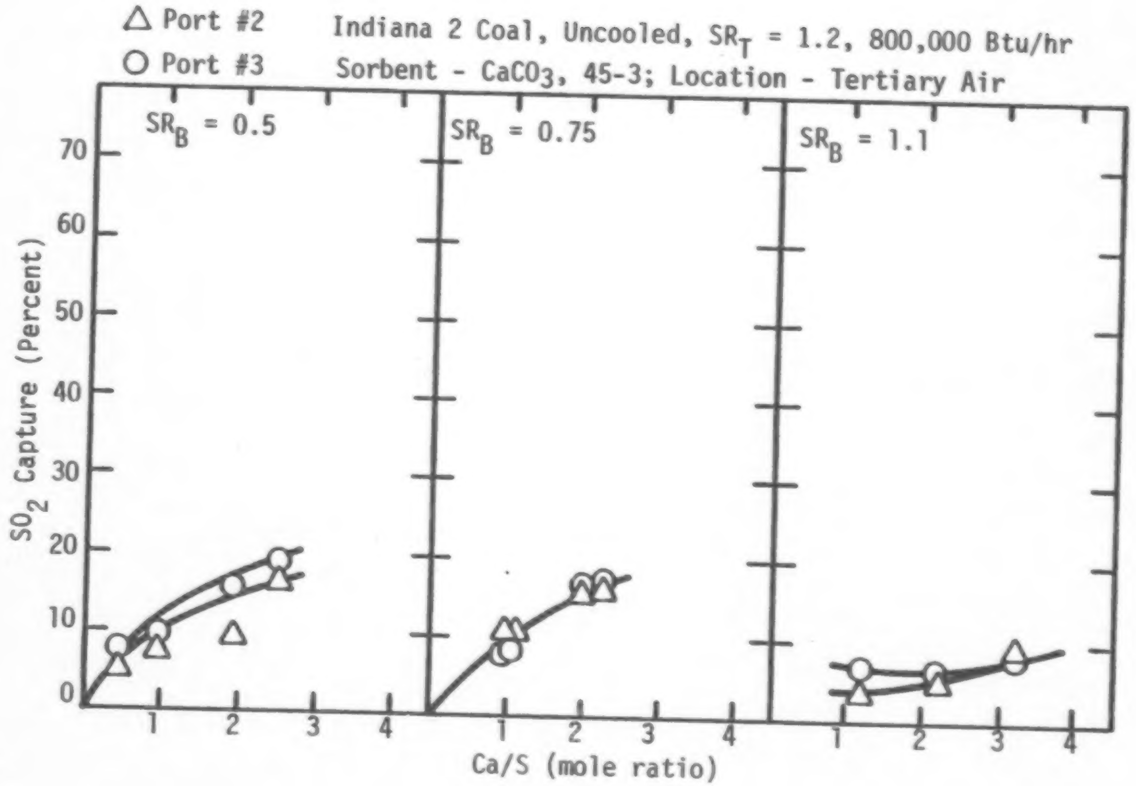
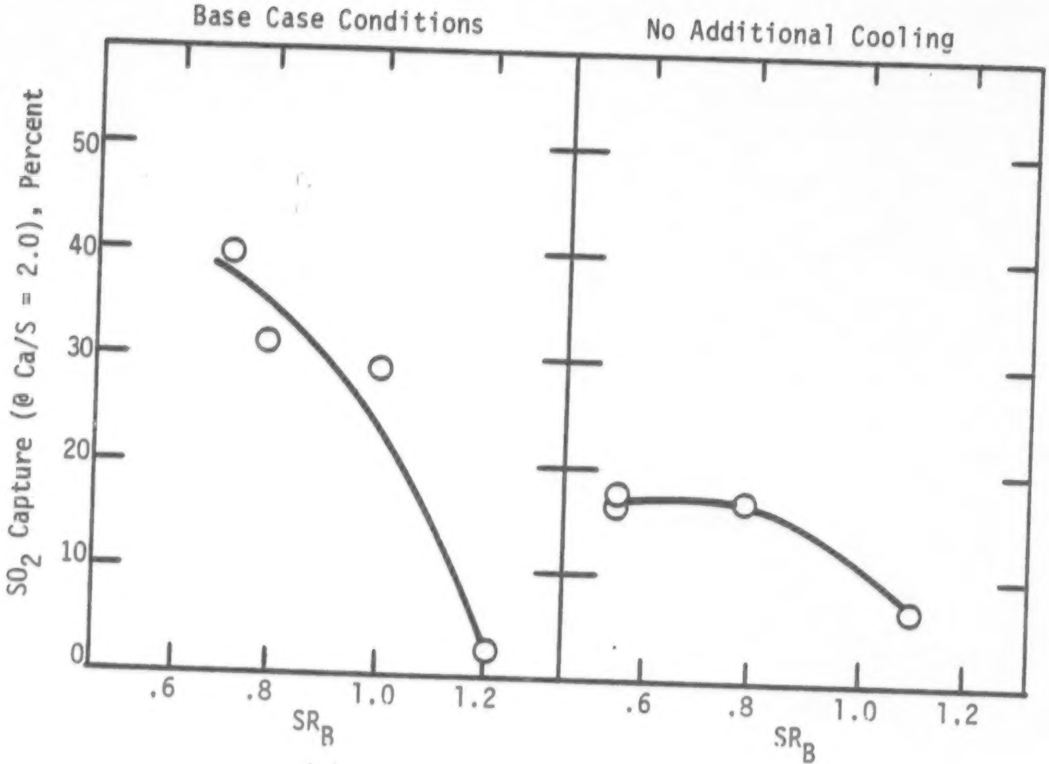


Figure 5-11. Influence of burner zone stoichiometry - uncooled.



(a)

Date: 8/6, 8/7/81
Rate: 825,000 Btu/hr
Cooling: 130,000 Btu/hr
SR_P: 0.2
SR_B: As Shown
SR_T: 1.2
Coal: Indiana 2 (2.5%S)
Sample Port: #3
Sorbent: $CaCO_3$, 45-3
Injection Loc.: Tertiary Air

(b)

Date: 7/1, 7/2, 7/7/81
Rate: 830,000 Btu/hr
Cooling: None
SR_P: 0.2
SR_B: As Shown
SR_T: 1.2
Coal: Indiana 2 (2.5%S)
Sample Port: #3
Sorbent: $CaCO_3$, 45-3
Injection Loc.: Tertiary Air

Figure 5-12. Summary of burner zone stoichiometry results.

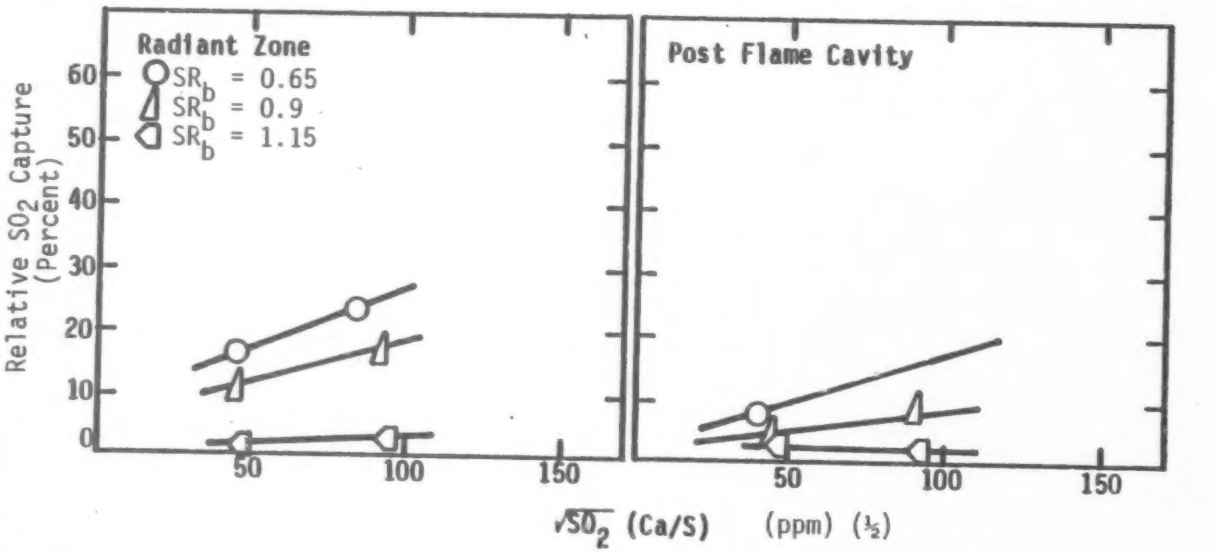
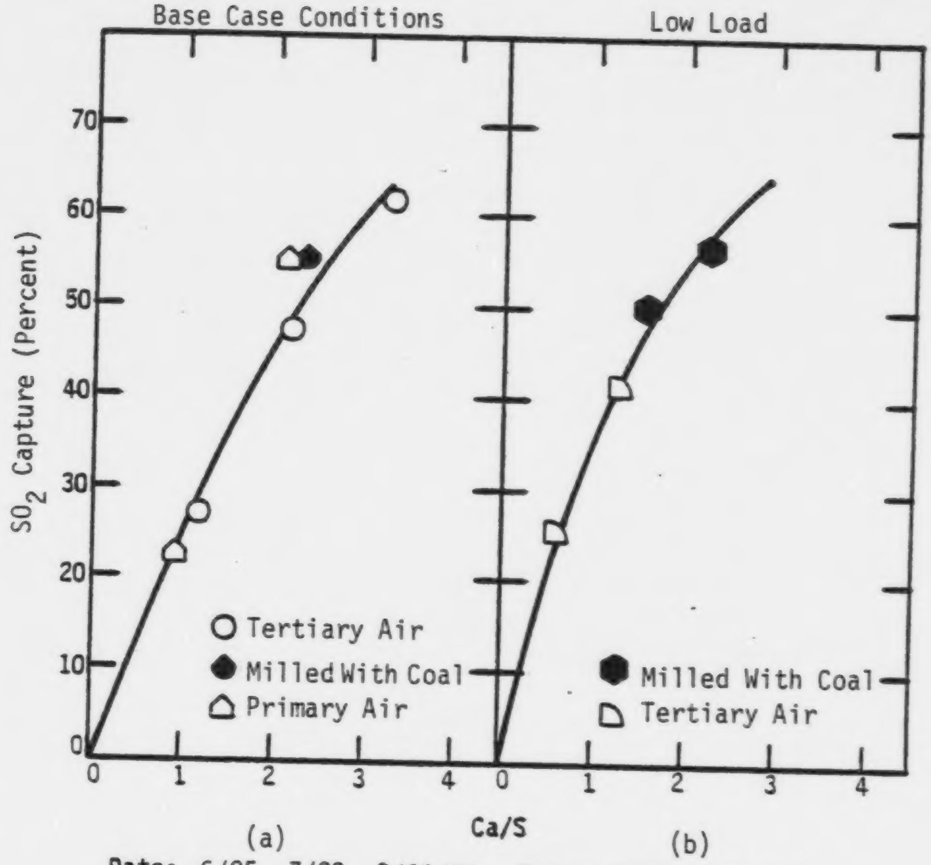


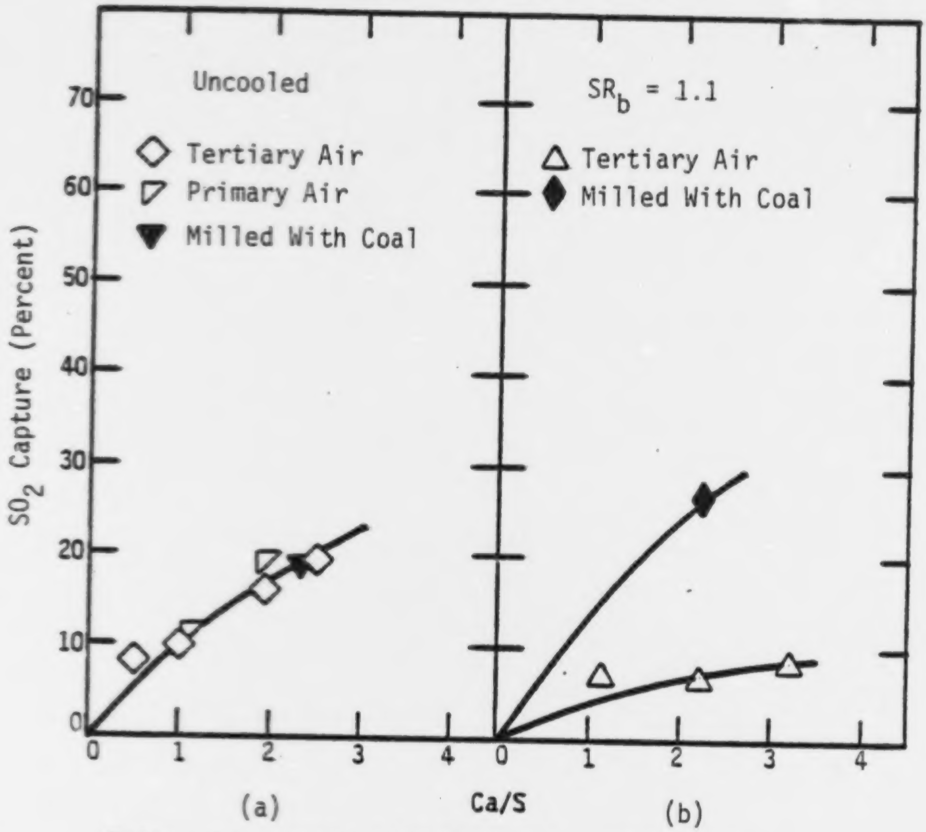
Figure 5-13. Effect of burner zone stoichiometry on zone capture (conditions as in Figure 5-12b).



Date: 6/25, 7/29, 8/21/81
Rate: 800,000 Btu/hr
Cooling: 120,000 Btu/hr
SR_P: 0.2
SR_B: 0.6
SR_T: 1.2
Coal: Indiana 2 (2.5%S)
Sample Port: #3
Sorbent: $CaCO_3$, 45-3
Injection Loc.: As Shown

Date: 6/26, 8/14/81
Rate: 570,000 Btu/hr
Cooling: 70,000 Btu/hr
SR_P: 0.25
SR_B: 0.6
SR_T: 1.2
Coal: Indiana 2 (2.5%S)
Sample Port: #3
Sorbent: $CaCO_3$, 45-3
Injection Loc.: As Shown

Figure 5-14. Effect of sorbent location.



Date: 7/1, 8/10, 8/18/81
Rate: 800,000 Btu/hr
Cooling: None
SRp: 0.2
SRB: 0.6
SRT: 1.2
Coal: Indiana 2 (2.5%S)
Sample Port: #3
Sorbent: $CaCO_3$, 45-3
Injection Loc.: As Shown

Date: 7/7, 8/18/81
Rate: 800,000 Btu/hr
Cooling: None
SRp: 0.2
SRB: 1.1
SRT: 1.2
Coal: Indiana 2 (2.5%S)
Sample Port: #3
Sorbent: $CaCO_3$, 45-3
Injection Loc.: As Shown

Figure 5-15. Effect of sorbent location - uncooled conditions.

(Figure 5-16). This reduction results in increased residence times within both the flame zone and the postflame cavity. As the temperature profile in Figure 5-16 shows, it also somewhat decreases the maximum wall temperatures measured throughout the furnace. The effect of firing rate on sulfur capture in the BSF without any cooling is shown by the data in Figure 5-17a and the effect of firing rate on sulfur capture when the sorbent was injected with the fuel is shown by the data in Figure 5-17b. Under uncooled conditions a decrease in load increased sulfur-capture just as it did for the cooled conditions. Unexpectedly, firing rate did not affect sulfur capture when the sorbent was injected into the cooled furnace with the fuel. It is not clear why decreasing the furnace load increased capture when the sorbent was injected with the tertiary air and did not increase capture when the sorbent was injected with the fuel.

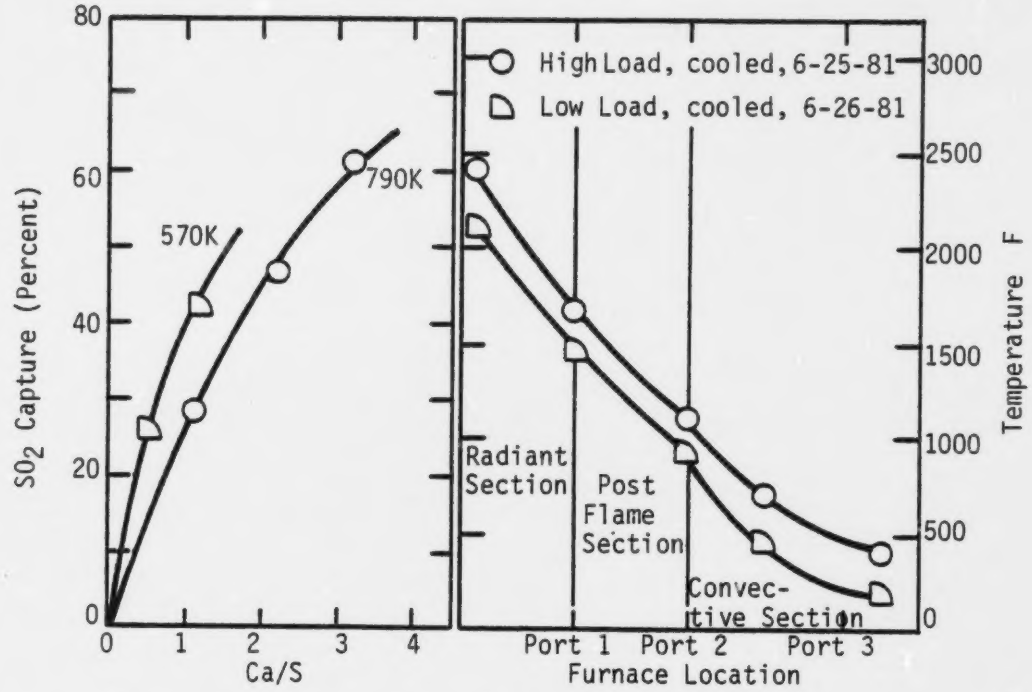
Figure 5-18 shows the effect of firing rate variations on differential capture in the radiant and postflame zone for the high and low load cases. Reducing the firing rate significantly increases the percentage capture in the radiant zone; however, it has essentially no effect on sorbent effectiveness in the postflame cavity. This suggests that both conditions produce a material that is equally effective in the lower temperature regions.

Influence of Tertiary Air Velocity

The diameter of the tertiary air ports was varied to change the tertiary air injection velocity. The data (Figure 5-19) indicate that the velocity could be decreased by about 50 percent from the standard case (50 ft/sec) with no effect on the sulfur capture. However, increasing the velocity from the base case conditions significantly increased the sorbent effectiveness. Figure 5-20 shows the effect of tertiary air velocity on the relative zone capture. These results suggest that injecting the sorbent in a high-velocity air jet increases the reactivity of the sorbent through the radiant and postflame regions.

Influence of Overall Excess Air

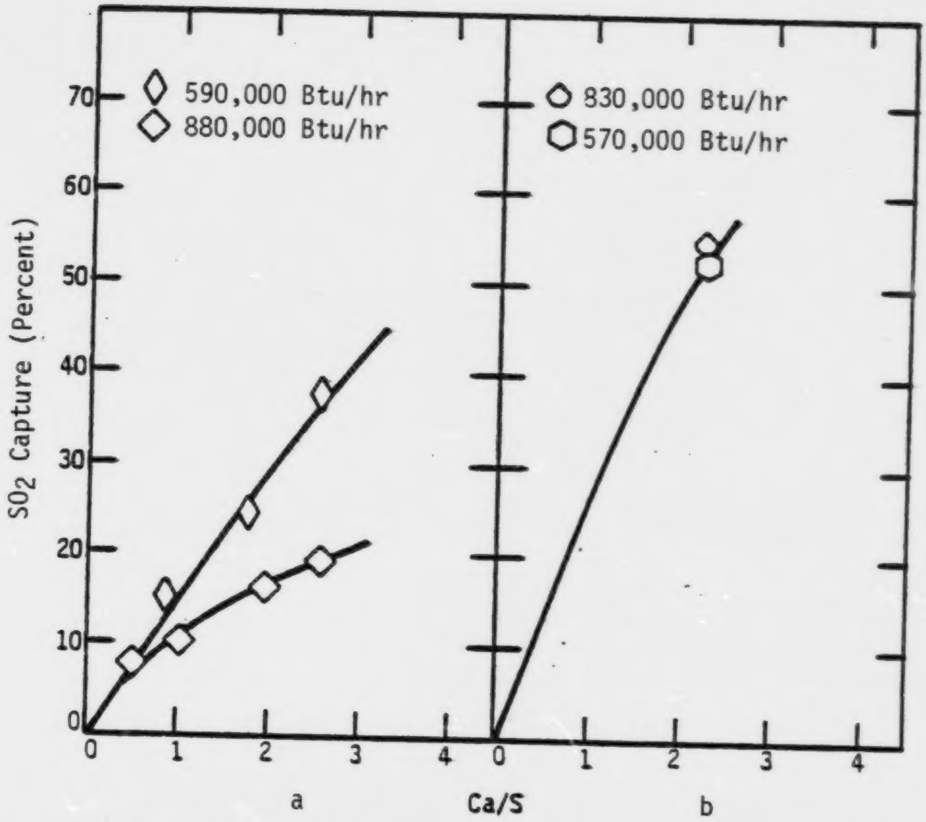
To establish the role of overall stoichiometry, the total air flow rate was increased (by increasing the tertiary air flow rate) to produce a 50 percent excess air case (SR_T = 1.5). The results from this experiment are shown



Date: As Shown
Rate: As Shown
SR_P: 0.2
SR_B: 0.6
SR_T: 1.2

Sorbent: $CaCO_3$, 45-3
Injection Loc.: Tertiary Air
Cooling: ~100,000 Btu/hr
Coal: Indiana 2 (2.5%S)

Figure 5-16. Influence of firing rate on sulfur capture.



Date: 7/1/, 7/4/81
Rate: As Shown
Cooling: None
SR_P: 0.2
SR_B: 0.6
SR_T: 1.2
Coal: Indiana 2 (2.5%S)
Sample Port: #3
Sorbent: $CaCO_3$, 45-3
Injection Loc.: Tertiary Air

Date: 8/14, 8/21/81
Rate: As Shown
Cooling: ~13%
SR_P: 0.2
SR_B: 0.6
SR_T: 1.2
Coal: Indiana 2 (2.5%S)
Sample Port: #3
Sorbent: $CaCO_3$, 45-3
Injection Loc.: Milled With Coal

Figure 5-17. Influence of firing rate on sulfur capture: uncooled, and sorbent with coal.

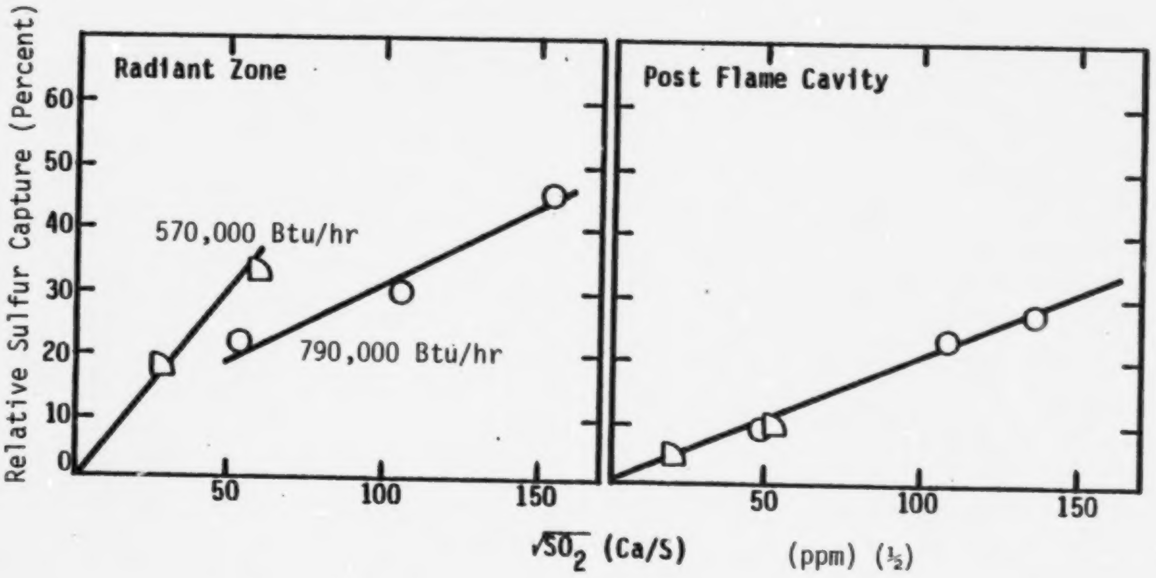
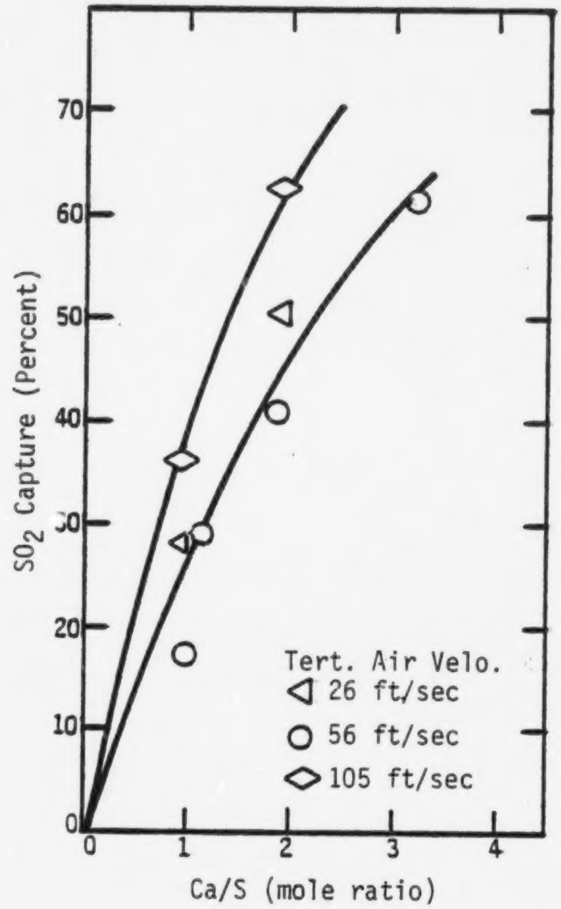


Figure 5-18. Effect of firing rate on zone capture (conditions as in Figure 5-16).



Date: 8/19, 8/20/81
Rate: 800,000 Btu/hr
Cooling: 110,000 Btu/hr
SR$_P$: 0.2
SR$_B$: 0.6
SR$_T$: 1.2

Coal: Indiana 2 (2.5%S)
Sample Port: #3
Sorbent: CaCO$_3$, 45-3
Injection Loc.: Tertiary Air

Figure 5-19. Effect of tertiary air velocity.

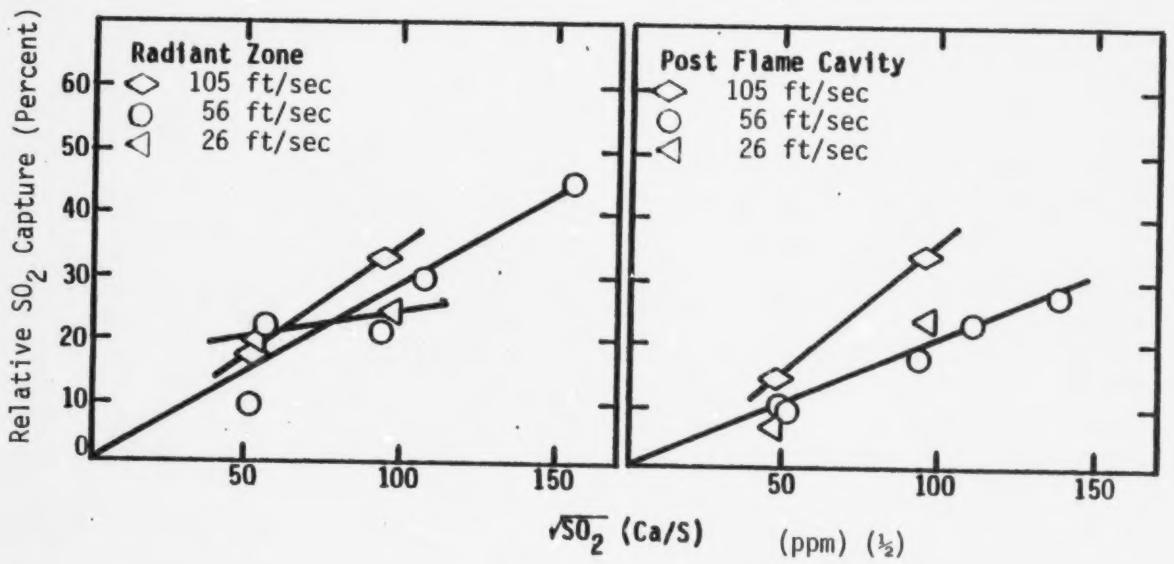


Figure 5-20. Effect of tertiary air velocity on zone capture (conditions as in Figure 5-19).

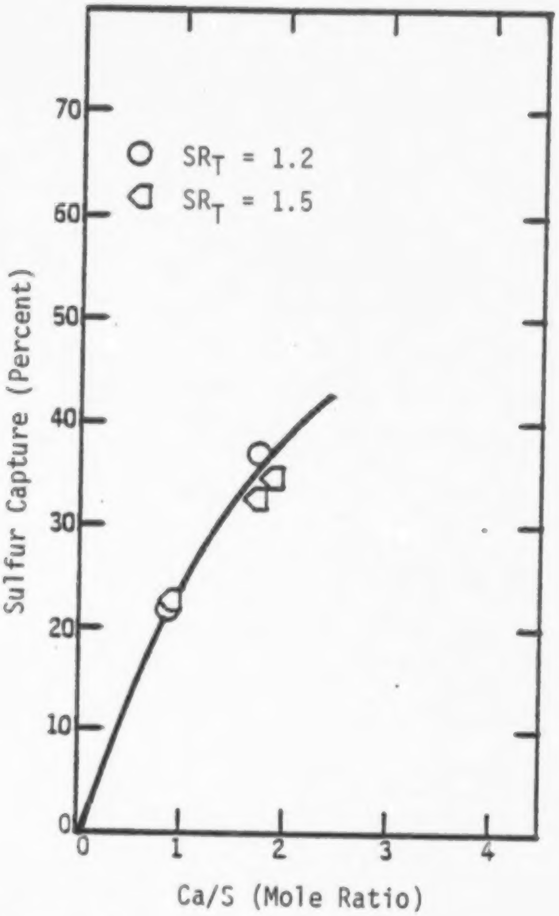
Figure 5-21. The data indicate that overall excess air had little effect on sulfur capture by limestone. A slight increase in sorbent effectiveness might have been expected based on the associated increase in tertiary air velocity and decrease in gas temperature; however, a decrease in sulfur capture due to reduced residence time and increased dilution may also have been expected; the effects may have cancelled each other.

Results, Physically Staged Studies (A-2)

The effect of various parameters on sulfur capture under predominantly fuel-rich conditions was investigated using the BSF fired in the physically staged mode. The furnace was fired with Indiana 2 coal, part of the combustion air was added with the fuel at the burner, the remainder of the fuel was added downstream at the exit of the radiant furnace. Sorbent could be added with the fuel or the staging air. The BSF was modified slightly, as shown in Figure 5-22, for these experiments. Fuel, air, and sorbent injection locations as well as sampling locations are indicated. The effect of first stage (rich zone) stoichiometry on sulfur evolution from the coal and on sorbent utilization, and the effect of various combustion parameters on sulfur capture were investigated. The parameters of interest included:

- Load
- Sorbent Injection Location (with fuel, staging air, or into rich zone at base of PFC)
- Radiant Zone Cooling

Adding only part of the combustion air through the burner had a marked impact on the thermal history of the sorbent and combustion gases. The data in Figure 5-23 show typical time/temperature profiles for two cases and demonstrate the impact of external staging on the furnace thermal profile. Adding only 60 percent of the combustion air at the burner results in a lower radiant zone temperature and a much longer radiant zone residence time than when 114 percent of the theoretical combustion air is added at the burner. The physical staging also causes increased postflame and convective section temperatures, because a significant portion of the fuel heat release is taking place in the second stage.



Date: 8/7/81
Rate: 840,000 Btu/hr
Cooling: 135,000 Btu/hr
SR_P: 0.2
SR_B: 0.6
SR_T: As Shown

Coal: Indiana 2 (2.5%S)
Sample Port: #3
Sorbent: $CaCO_3$, 45-3
Injection Loc.: Tertiary Air

Figure 5-21. Effect of increased excess air.

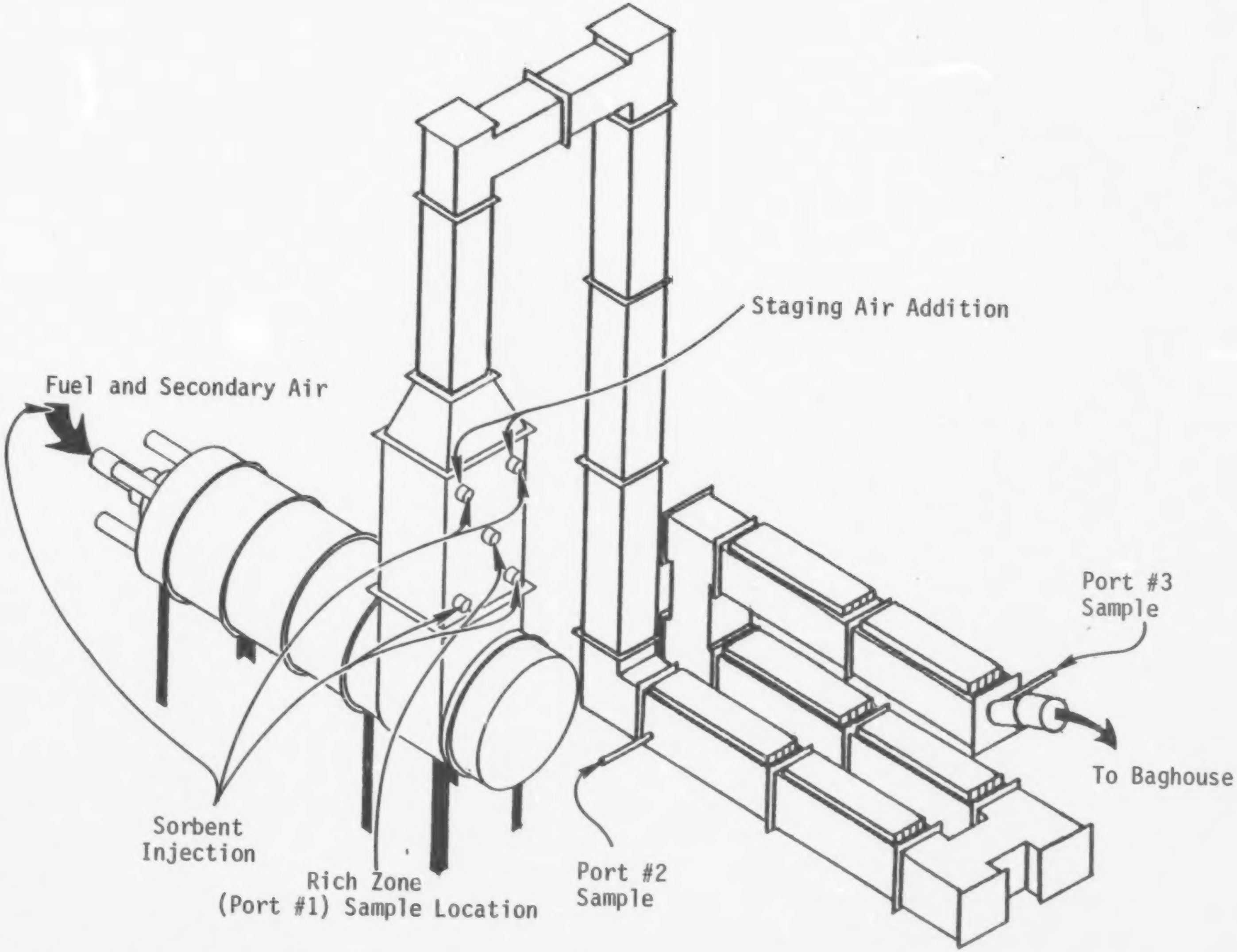
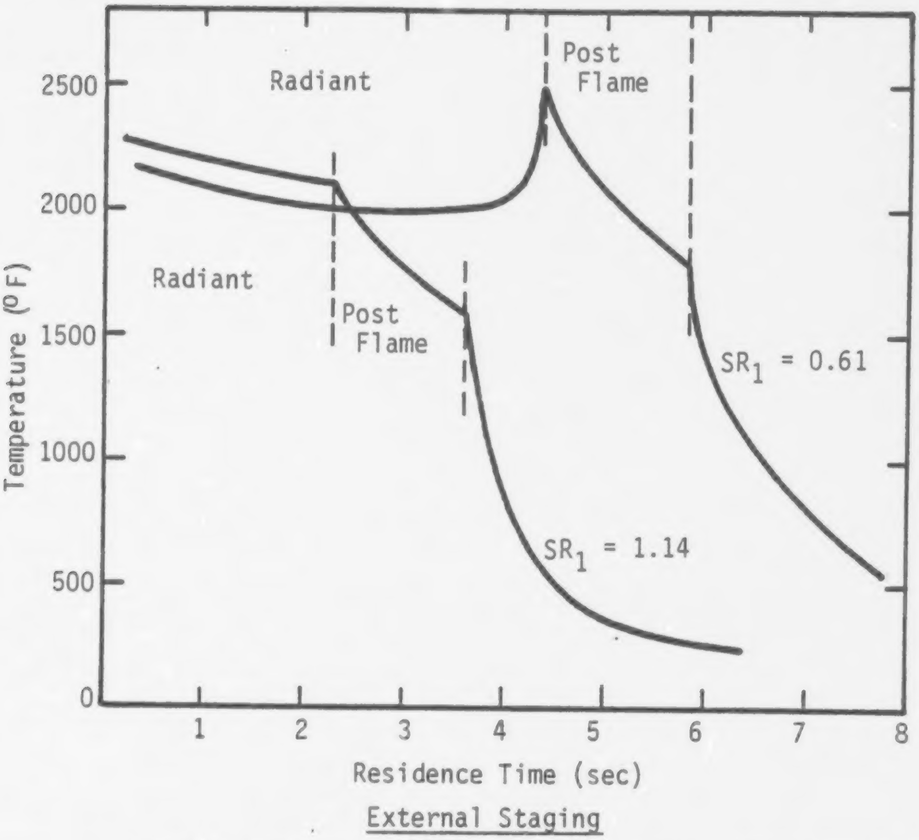

Staging Air Addition
Fuel and Secondary Air
Port #3
Sample
To Baghouse
Sorbent
Injection
Rich Zone
(Port #1) Sample Location
Port #2
Sample

Figure 5-22. BSF configuration for physically (external) staged studies (A-2).



External Staging

Coal: Indiana
Rate: 800,000 Btu/hr
SR_1: Shown
SR_T: 1.15
Ca/S: ---

Sample Port: Shown
Sorbent: None
Injection Loc.: ---
Cooling: Yes

Figure 5-23. Impact of external staging on thermal environment, BSF.

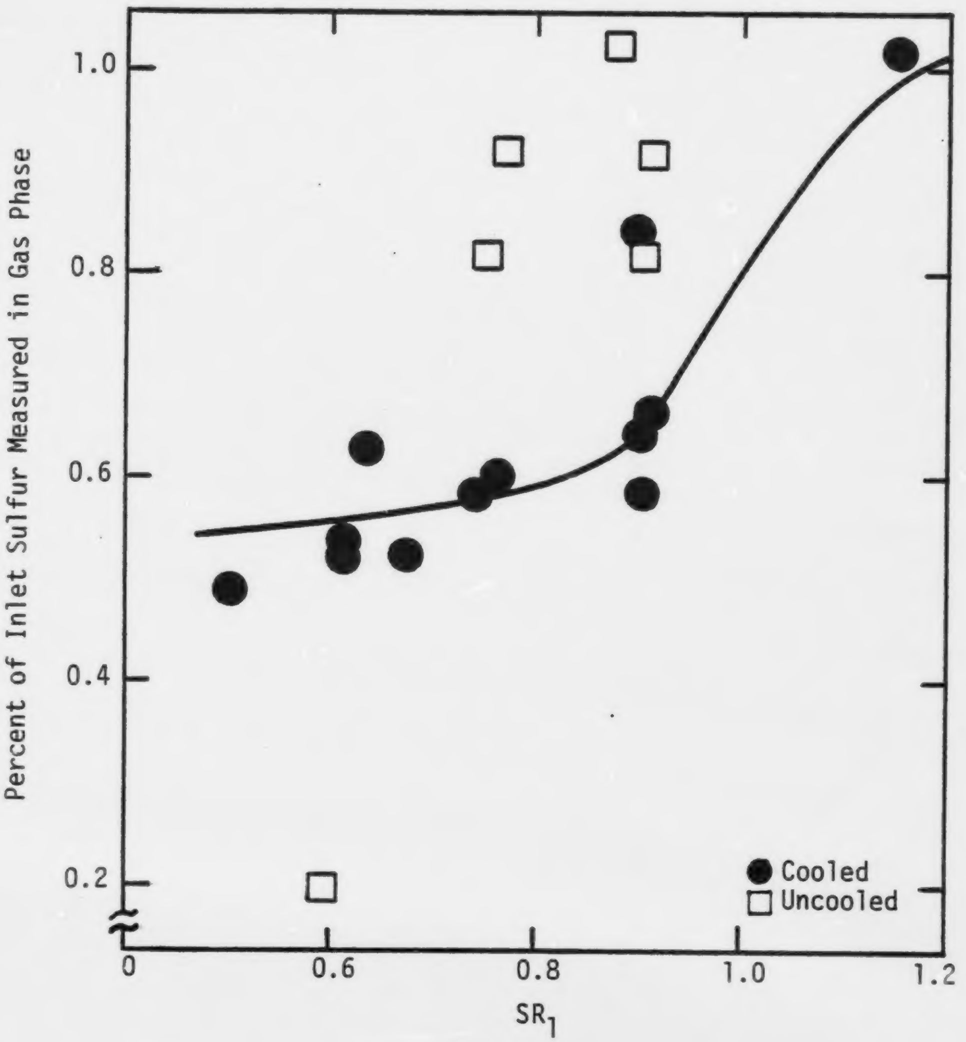
Sulfur Evolution and Speciation, Physically Staged Conditions

The first stage stoichiometry affected the amount and form of sulfur found in the gas phase in the fuel rich zone. Figures 5-24, 5-25, and 5-26 show the total gaseous sulfur (based on the sum of the sulfur species measured and the theoretical gas phase sulfur) measured in the rich zone and measured sulfur species distribution as a function of first zone stoichiometry with and without cooling in the radiant furnace. It is clear that both rich zone stoichiometry and thermal environment affect the sulfur gasification efficiency and the sulfur species distribution in the rich zone. Equilibrium calculations predict essentially all SO_2 under fuel lean conditions ($SR > 1.0$) and all H_2S under fuel rich conditions ($SR < 1.0$), while the measurements indicated that SO_2 was considerably more predominant and COS concentrations higher than expected under fuel-rich conditions in these coal flames.

The data in Figure 5-27 show the influence of first stage stoichiometry on sulfur capture and post-flame cavity (PFC) temperature (as indicated by the wall temperature at the exit of the PFC). Staging the combustion air changes the fuel heat release pattern and, therefore, the furnace temperature profile. The increased post-flame cavity temperatures at low SR_1's were not surprising, but the observed decrease in sulfur capture was not expected. The drop in sorbent utilization at highly staged conditions may be due to:

- Sorbent deactivation by the second stage flame
- High regeneration (decomposition of reacted sorbent from CaS to CaO + SO_2), because of the high second stage flame temperatures
- Changed sulfur evolution pattern (large amounts of sulfur being evolved in the second stage) affecting sulfur capture

The data generated on individual sulfur species capture by sorbent in the first stage is shown in Figure 5-28. The data can only be interpreted in a general manner, but they indicate that no single species is more favorably captured.

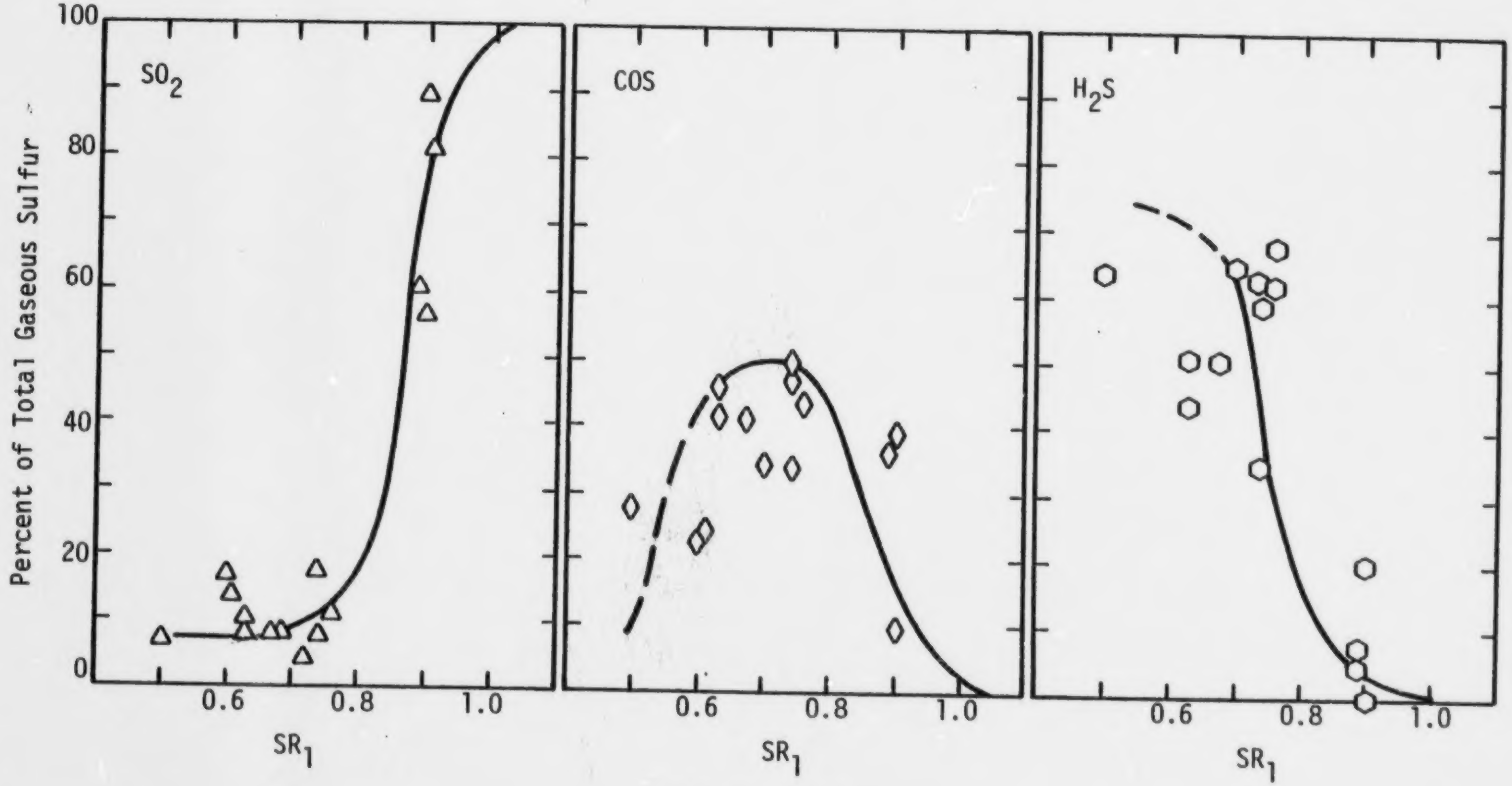


External Staging

Coal: Indiana
Rate: 800,000 Btu/hr
SR_1: Shown
SR_T: 1.2
Ca/S: ---

Sample Port: #1 (rich zone)
Sorbent: None
Injection Location: ---
Cooling: Shown

Figure 5-24. Effect of first stage stoichiometry on sulfur evolution from Indiana coal.

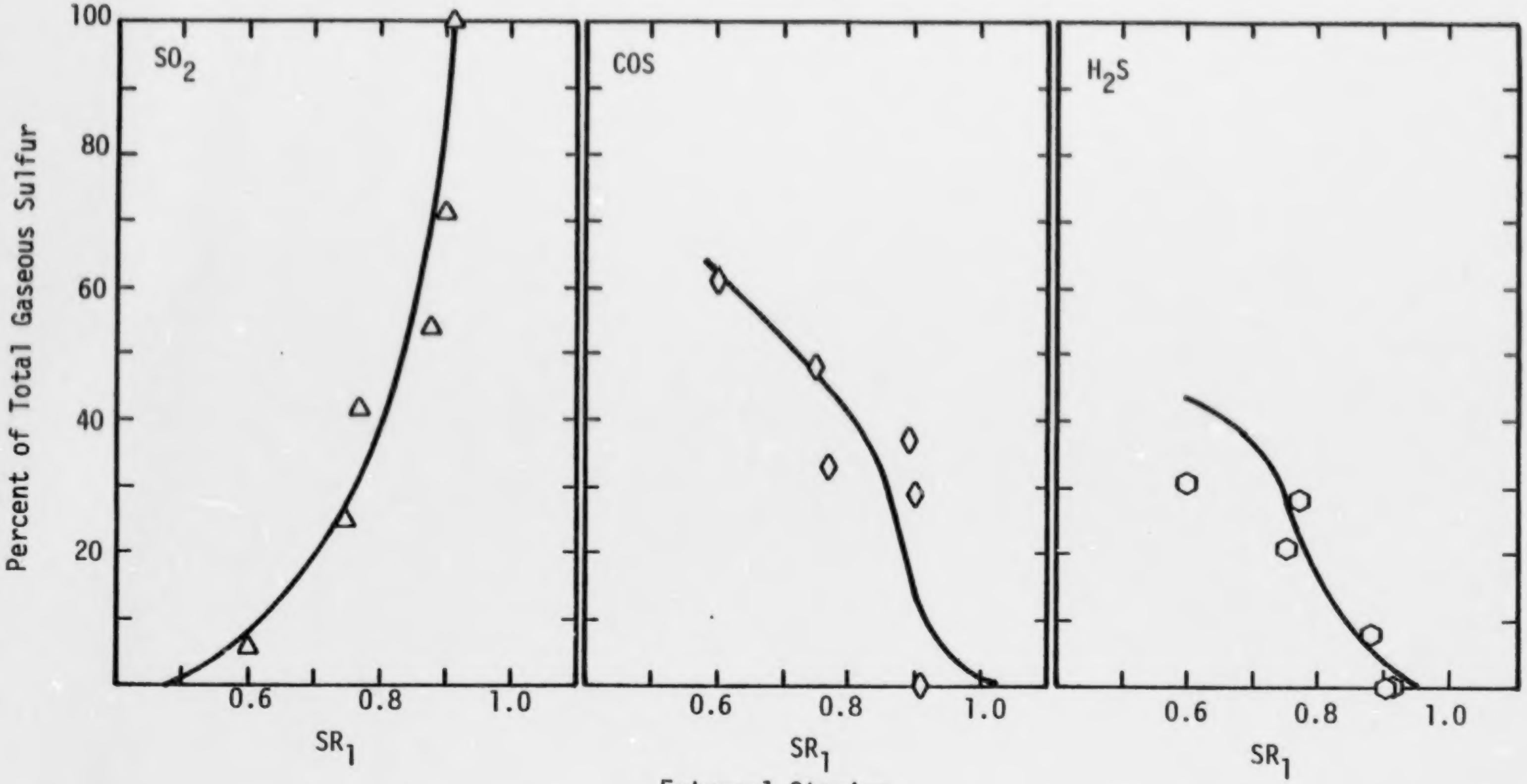


External Staging

Coal: Indiana
Rate: 800,000 Btu/hr
SR$_1$: Shown
SR$_T$: 1.2
Ca/S: ---

Sample Port: #1 (Rich Zone)
Sorbent: None
Injection Location: ---
Cooling: Yes

Figure 5-25. Effect of first stage stoichiometry on sulfur species distribution, cooled.

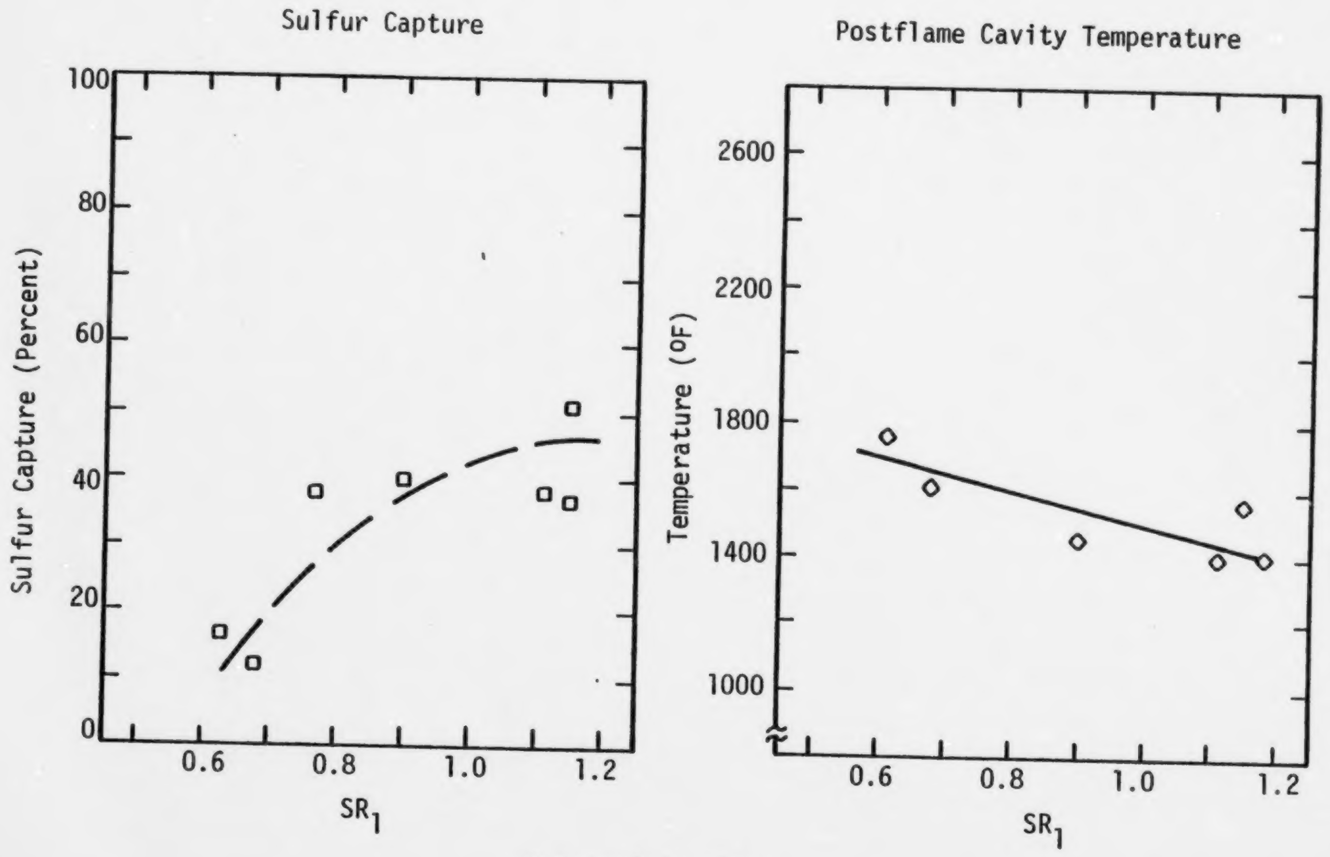


External Staging

Coal: Indiana
Rate: 800,000 Btu/hr
SR_1: Shown
SR_T: 1.2
Ca/S: ---

Sample Port: #1 (Rich Zone)
Sorbent: None
Injection Location: ---
Cooling: No

Figure 5-26. Effect of first stage stoichiometry on sulfur species distribution - uncooled.

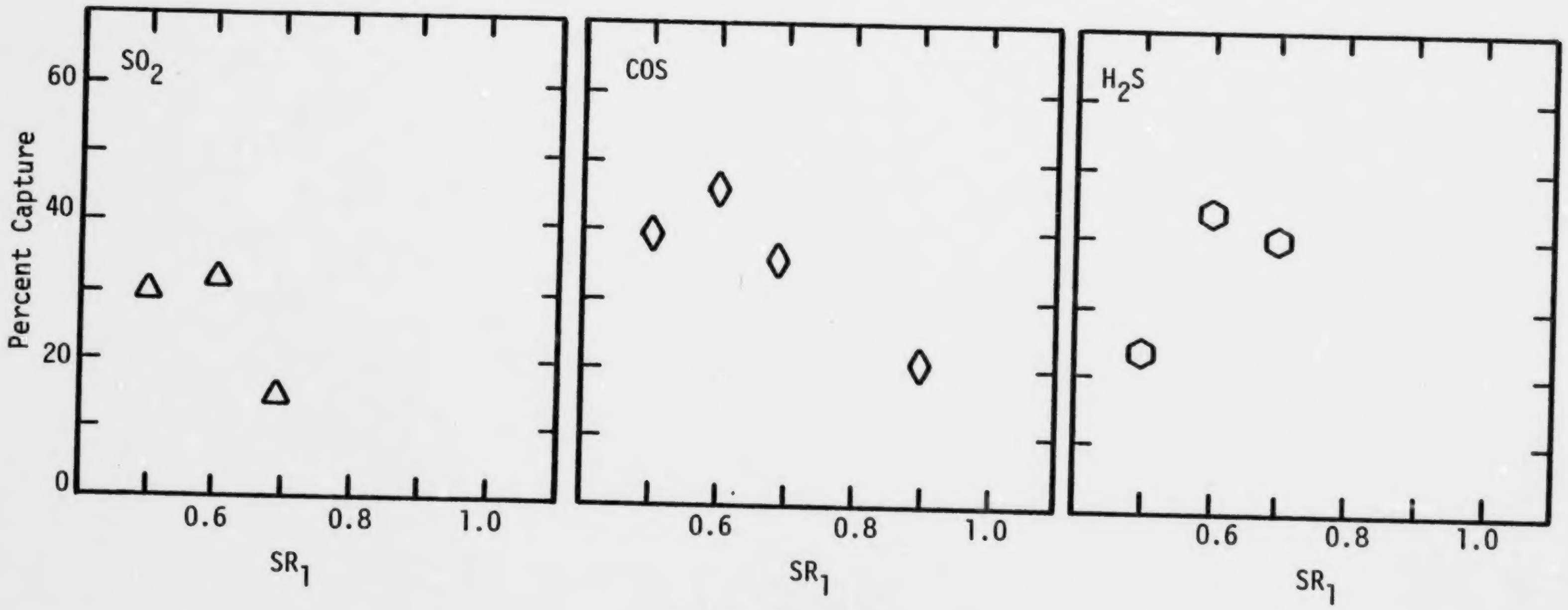


External Staging

Coal: Indiana
Rate: 800,000 Btu/hr
SR_1: Shown
SR_T: 1.2
Ca/S: 2.1

Sample Port: #3
Sorbent: $CaCO_3$, 45-3
Injection Location: Primary Air
Cooling: Yes

Figure 5-27. Effect of first stage stoichiometry on sulfur capture and post flame cavity temperature.



External Staging

Coal: Indiana
Rate: 800,000 Btu/hr
SR_1: Shown
SR_T: 1.2
Ca/S: 2.1

Sample Port: #1
Sorbent: $CaCO_3$, 45-3
Injection Location: Primary Air
Cooling: Yes

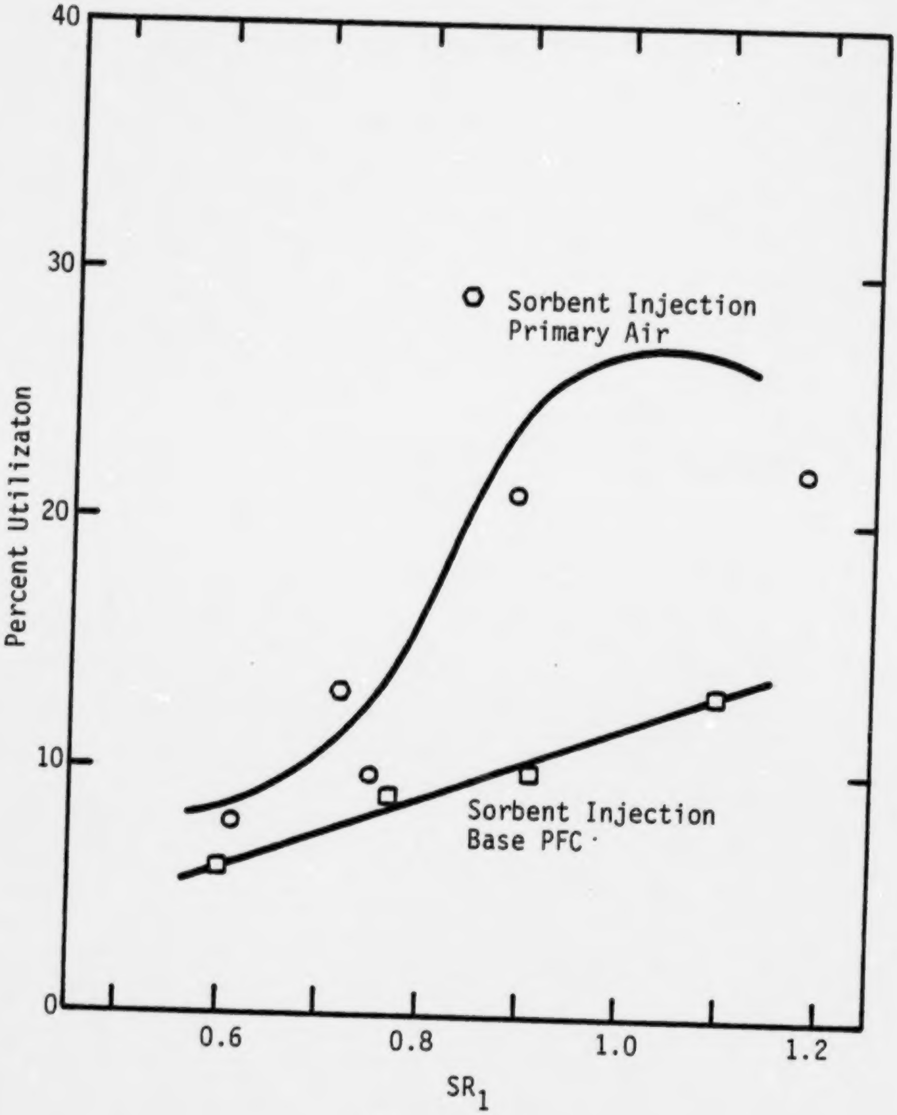
Figure 5-28. Effect of first stage stoichiometry on individual sulfur species captures.

The effect of sorbent injection location on sulfur capture in the physically staged mode was investigated by adding the sorbent with the coal in the primary air, injecting the sorbent in an inert carrier gas (N_2) at the base of the post-flame section or injecting the sorbent with the staging air. The external staging experiments were generally performed at only one calcium-to-sulfur ratio for each first stage stoichiometry. Slight changes in load and sorbent feed-rate resulted in some variation in the calcium-to-sulfur ratio during a run (set of different SR_1 conditions). In order to eliminate the variation in Ca/S ratio, results of some of the external staging studies are given in terms of percent utilization. Percent utilization is simply percent capture divided by the calcium-to-sulfur ratio.

The data plotted in Figure 5-29 compares sorbent utilization at several first-stage stoichiometries when the sorbent was injected with the fuel or with a nitrogen carrier at the base of the postflame section. The results were somewhat surprising. It was expected that injecting the sorbent at the base of the postflame cavity, before the staging air, would provide ideal conditions for a fast, direct reaction between $CaCO_3$ and H_2S, which, in turn, would give high sorbent utilization. The sorbent utilization for this injection mode was significantly lower than for sorbent injection with the coal. There are several possible explanations for this, including: the reaction time was decreased because the sorbent was injected at the base of the post-flame cavity, the injection mode (with N_2) gave poor mixing and/or poor calcination of the sorbent, or the sulfur had not yet evolved from the coal to react with the sorbent.

The effect of first-stage stoichiometry on sulfur capture when the sorbent was added with the fuel or with the staging air is shown by the data in Figure 5-30. Two observations can be made: first, the utilization of sorbent added with the fuel was very similar for the cooled (Figure 5-30) and uncooled cases (5-29), and second, sorbent injection location had little effect on sulfur capture even though injecting the sorbent with the staging air decreases sorbent residence time.

The observation that sorbent injection into the staging air gave surprisingly high sulfur capture instigated an experiment where the

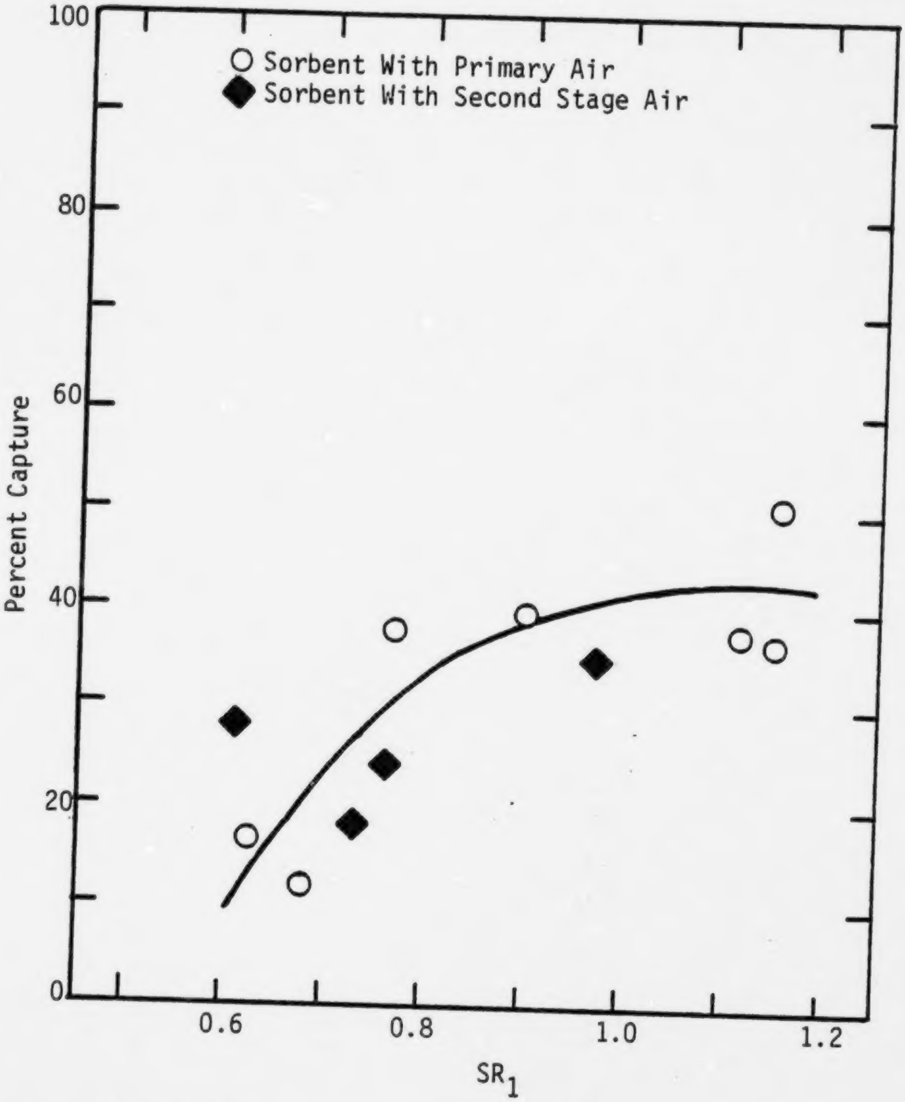


External Staging

Coal: Indiana
Rate: 800,000 Btu/hr
SR_1: Shown
SR_T: 1.2
Ca/S: 2.0 - 3.3

Sample Port: #3
Sorbent: $CaCO_3$, 45-3
Injection Loc.: Shown
Cooling: No
2nd Stage Air: Trans Top

Figure 5-29. Effect of sorbent injection method on sorbent utilization.



Coal: Indiana
Rate: 800,000 Btu/hr
SR_1: Shown
SR_T: 1.2

Ca/S: ~2.1
Sample Port: #3
Sorbent: $CaCO_3$, 45-3

Figure 5-30. Effect of sorbent location on sulfur capture, externally staged, cooled.

sorbent was injected with air rather than nitrogen at the base of the postflame section. Overall sorbent utilization is plotted as a function of first stage (not including the sorbent injection air) stoichiometry in Figure 5-31. At stoichiometries greater than 0.9 sorbent utilization for this injection mode are as high as when the sorbent was injected with the coal. Moreover, at lower rich zone stoichiometries sorbent utilization did not drop off as much as it did when injected with the coal. This difference may be the result of two factors:

- When the staging air is added in two portions peak temperatures in the second stage flame are reduced; this may in turn reduce sulfur regeneration and/or sorbent deadburning, and
- Char burnout takes place in a different region and may result in more of the coal sulfur being evolved where active sorbent is available.

The data plotted in Figure 5-32 show the effect of first-stage stoichiometry on sorbent utilization at low load. Reducing the firing rate reduced sulfur capture for the externally (physically) staged conditions, unlike the effect of firing rate under burner staged conditions.

The results of several of the externally staged experiments implied that char/sulfur retention retention in the fuel-rich region could account for low sorbent utilizations under highly staged conditions. In order to eliminate this effect, an experiment using propane doped with H_2S as the fuel was performed. The data in Figure 5-33 show sorbent utilization as a function of first-stage stoichiometry for the gas fired experiment.

Figure 5-34 shows the overall sorbent utilization for the propane-fired condition compared with the most similar coal-fired case. The data for the coal-fired condition have been corrected to actual gas phase stoichiometry (since part of the fuel in the first stage is still solid) for comparison with the propane data.

Summary--Combustion Parameter Screening Studies (Series A)

The effect of various combustion parameters on sulfur capture by dry sorbents was studied in the boiler simulator furnace. Results of the

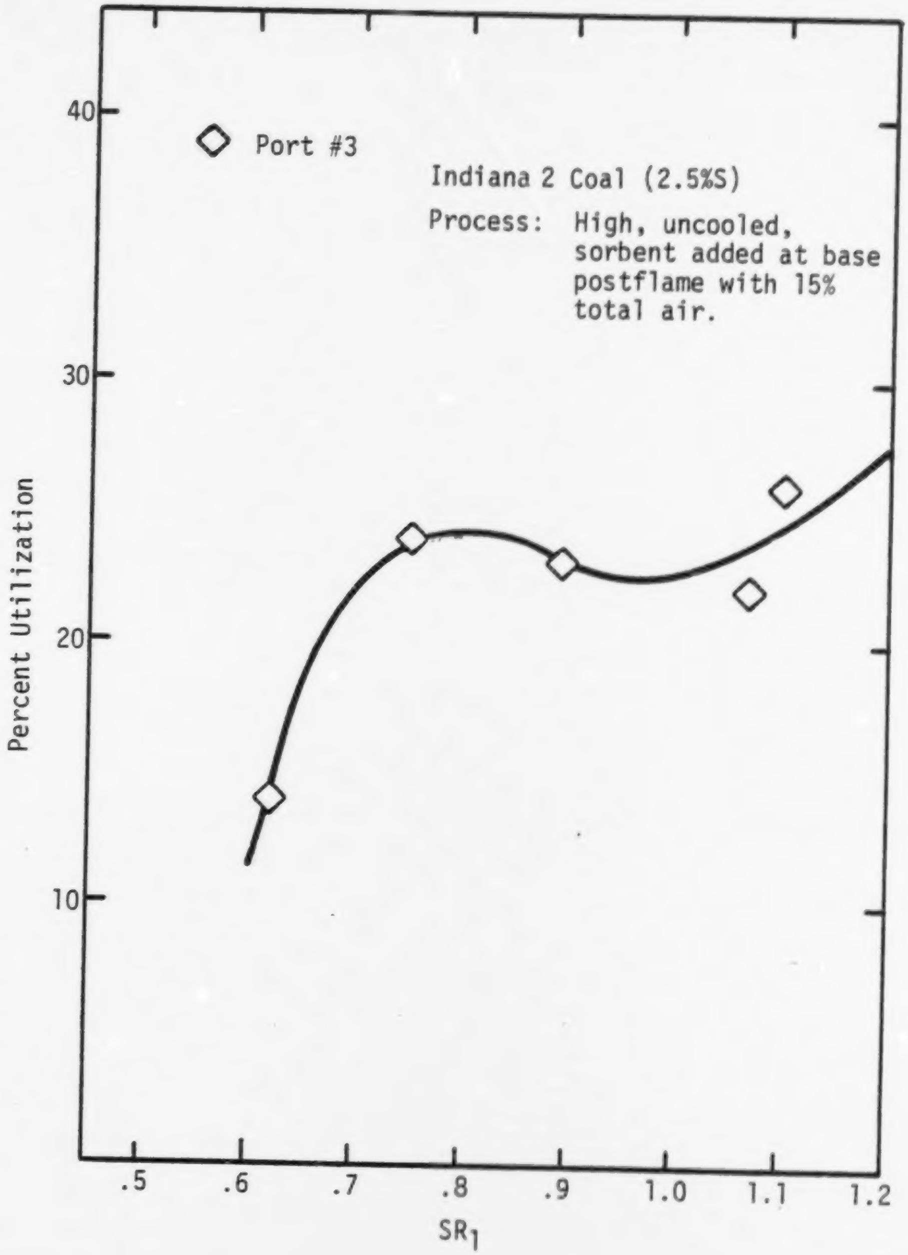


Figure 5-31. Effect of SR_1 on sorbent utilization, sorbent added with air at base of PFC.

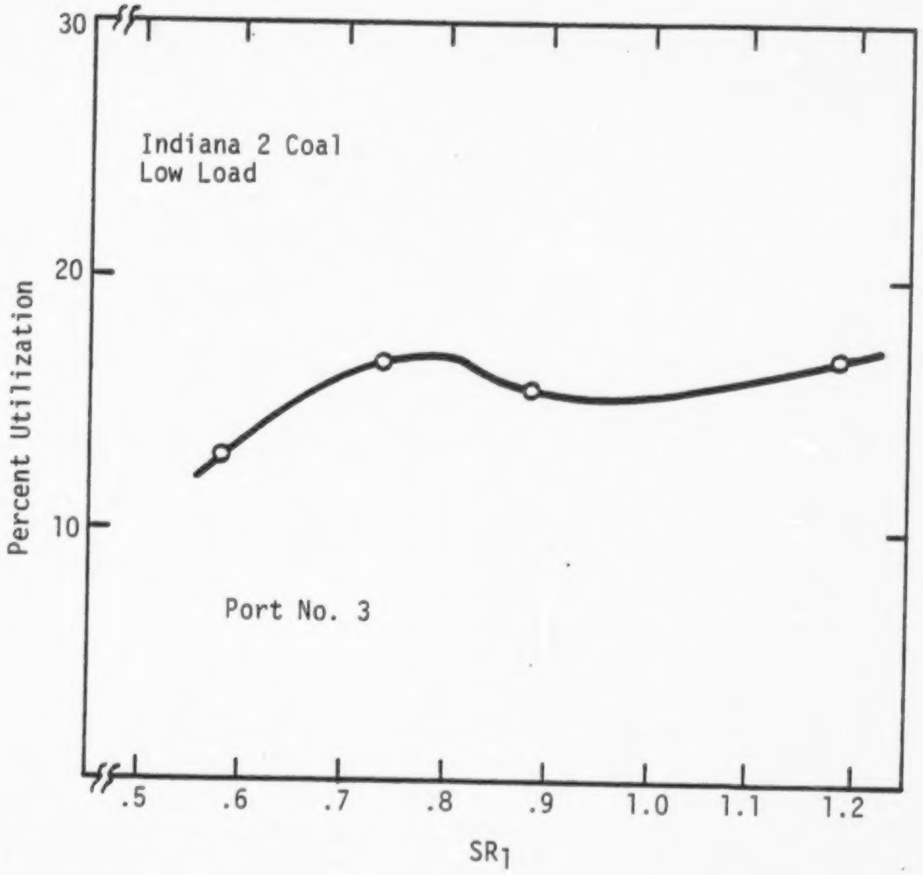


Figure 5-32. Effect of SR_1 on sorbent utilization, low load, uncooled.

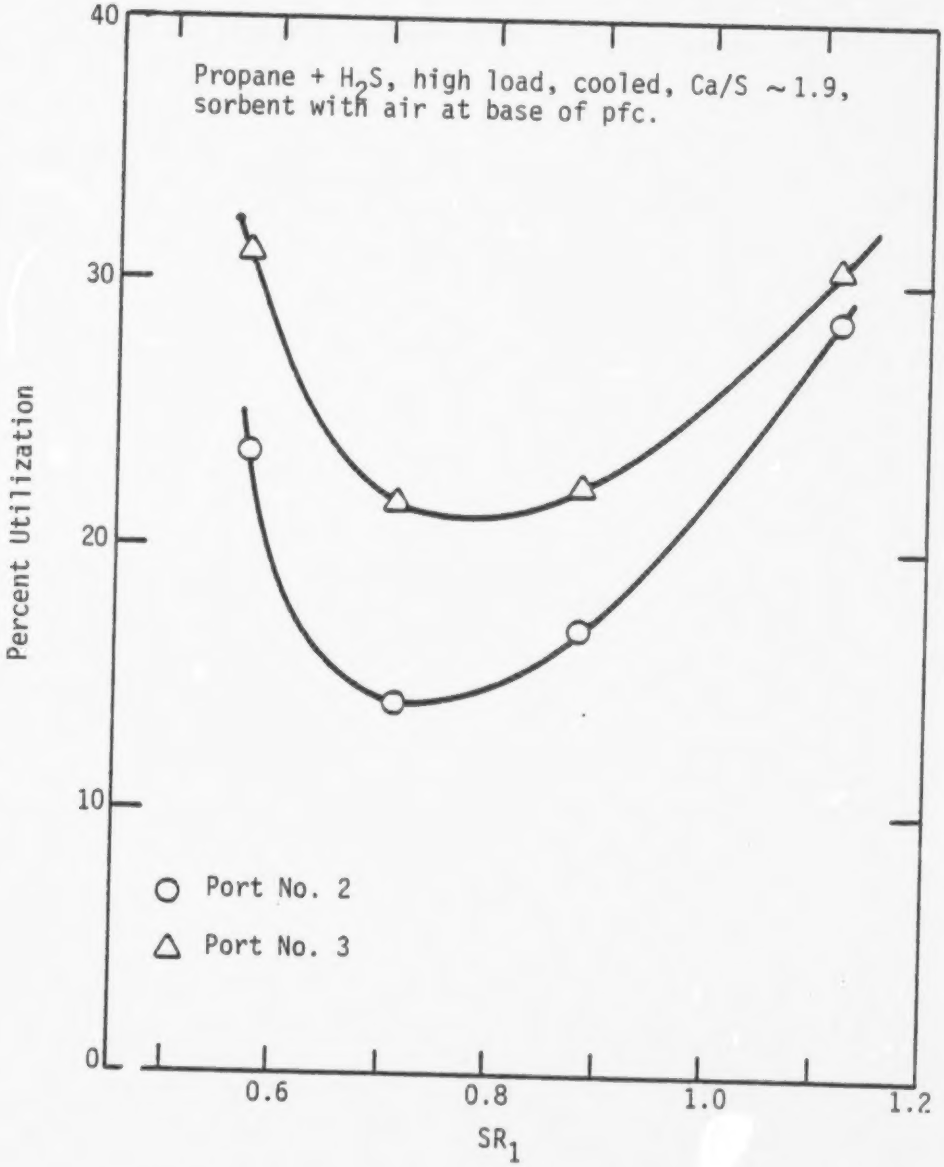


Figure 5-33. Effect of SR_1 on sorbent utilization for propane doped with H_2S (2500 ppm equilvalent exhaust SO_2).

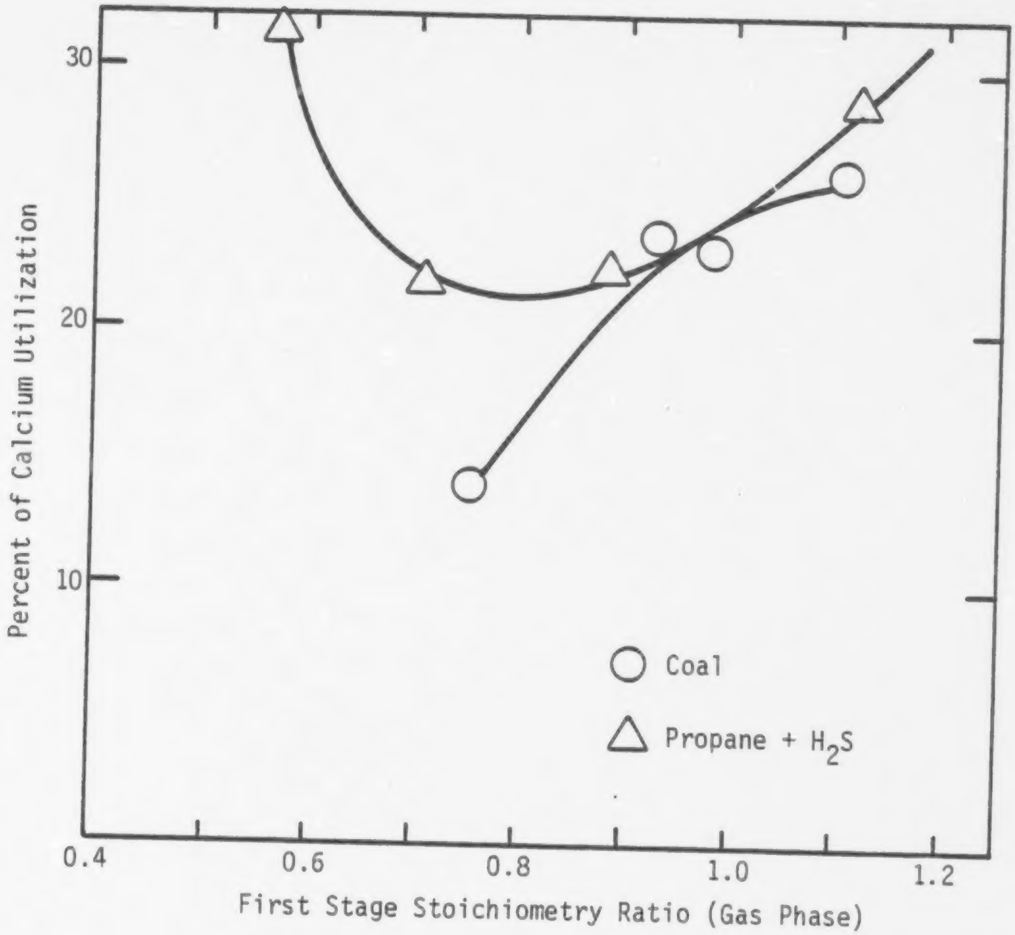


Figure 5-34. Capture and retention of sulfur under external staged conditions for coal and propane doped with H_2S, sorbent added with air at base of post flame section, uncooled.

parameter screening studies indicated that thermal environment has a strong effect on sulfur capture by dry sorbents injected directly into the furnace. The burner-staged experiments showed the influence of thermal environment most clearly; a reduction in the peak furnace temperature, due to cooling in the radiant furnace or to a reduction in load, increased sulfur capture significantly. Changes in other parameters such as sorbent location or injection velocity, had secondary effects on sulfur capture. The effect of thermal history under physically staged conditions was less evident. Changes in load or cooling in the radiant furnace were overshadowed by the changes in furnace temperature due to the physical staging itself. Physically staging the coal flame changed the furnace temperatures. The first stage, or fuel-rich region (which was the entire radiant furnace), was colder under external staged conditions, and the second-stage region (the first part of the postflame cavity) was ho-ter than under burner-staged conditions. The changes in thermal history due to the staging were greater than changes which could be effected by cooling or load reduction. First-stage stoichiometry and sorbent location affected sulfur capture under physically staged conditions. It was not clear if the effect of first-stage stoichiometry was due to the change in thermal history resulting from changed primary and secondary zone stoichiometries or to the effect of staging on sulfur evolution from the coal.

6.0 RESULTS, SULFUR CHEMISTRY AND THERMAL ENVIRONMENT STUDIES (SERIES B)

The second set of experiments was designed to: 1) investigate in more detail the effect of thermal environment on sulfur capture and 2) clarify the role of sulfur speciation and evolution from the coal in the sulfur capture process. The retention of sulfur in the char under fuel-rich, physically-staged conditions in the first set of experiments made the study of fuel-rich capture difficult to interpret. The first part of this series used propane doped with H_2S as the fuel in order to eliminate the char sulfur complication. The effect of stoichiometry, thermal environment, sulfur content, and sorbent location on sulfur capture from gaseous flames was investigated. The effect of thermal environment, including air preheat and flue gas recirculation (FGR) (simulated by nitrogen dilution), on sulfur capture from the coal flame was further investigated under both burner and physically staged conditions in the second portion of Series B.

The boiler simulator furnace was reconfigured before these experiments were started. The furnace was changed from horizontal to down-firing in order to reduce injection velocity limits and to facilitate the removal of slag. The post-flame section was rebuilt, using refractory rather than insulation-board lined walls. A transition between the radiant and post-flame sections was added and the area change from the radiant furnace to the convective sections (3.14 to 0.56 ft^2) was made in four steps rather than in two as in the original configuration. The new configuration is shown schematically in Figure 6-1. Sample points, staging air and sorbent injection locations are indicated. (These changes are described in detail in Appendix B).

A second batch of Indiana coal was obtained for this testing. The second batch was considerably different than the Indiana coal used in the first (Series A) set of experiments. The compositions of these two Indiana coals are summarized in Table 6-1. The most significant difference was the coal sulfur content, which changed from

				No Preheat No Cooling			No Preheat						No Preheat H_2S Inj. Postflame Radial Cooling	
							Radiant Zone Cooling (Top)			Postflame Cooling				
				Sorbent Location			Sorbent Location			Sorbent Location			Sorbent Loc.	
				Burner	Post-Flame	Second Stage	Burner	Post-Flame	Second Stage	Burner	Post-Flame	Second Stage	Burner	Post-Flame
Fuel Sulfur Content	1%	SR_1	0.5				X				2			
			0.7				X				2			
			0.9				X				2			
			1.1				X				2			
	Match Ind. (2%)	SR_1	0.5	X*	X	X*	X	X	2	X	Ø			
			0.7	X*	X	X*	X	X	2	X	Ø		Ø	Ø
			0.9	X*	X	X*	X	X	2	X	Ø		Ø	Ø
			1.1	X*	X	X*	X	X	2	X	Ø		Ø	Ø
	3%	SR_1	0.5				2				2		Ø	Ø
			0.7				2				2			
			0.9				2				2			
			1.1				2				2			

2 - should be considered after √ are completed

√ - Planned
X - Completed

Ø - Omitted (little interest)
* - Added

Figure 6-1. Test matrix, sulfur chemistry/thermal environment studies (B-1) propane fired.

TABLE 6-1. FUEL CHARACTERISTICS--COMPARISON OF INDIANA COALS

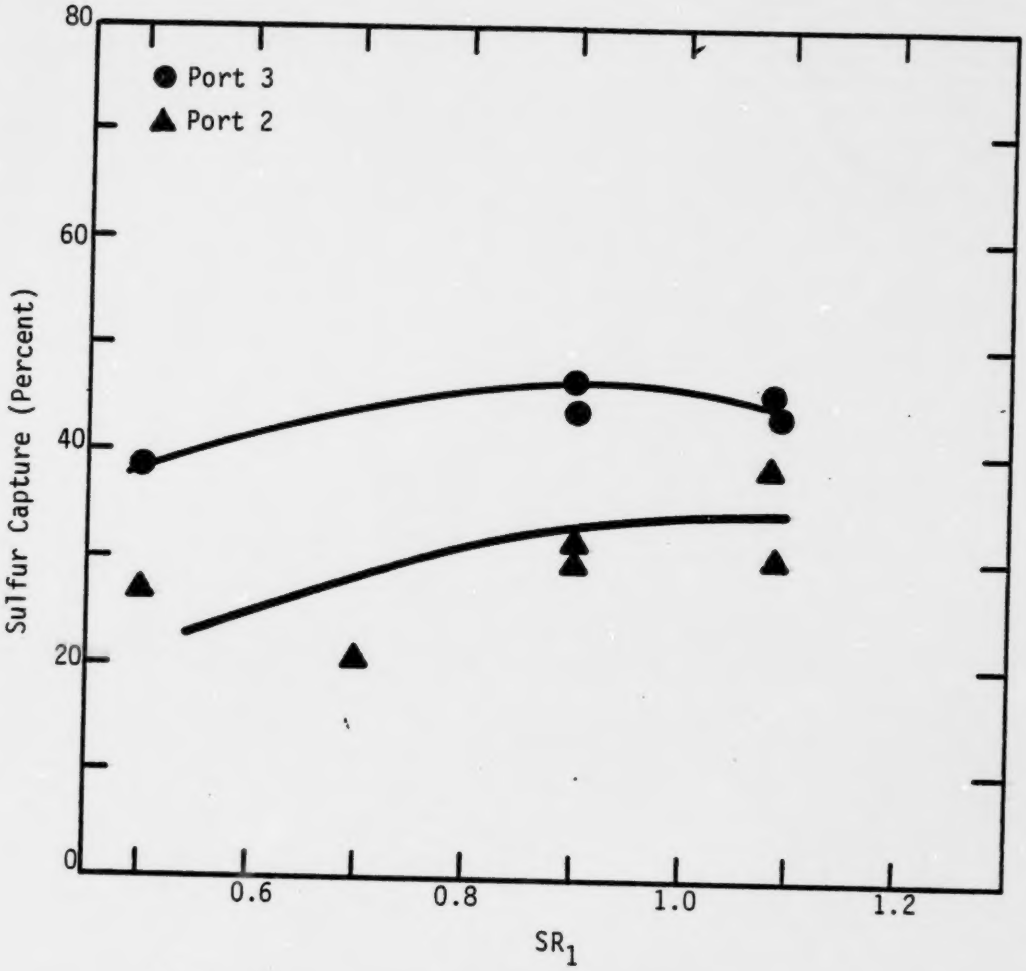
	Indiana 2	Indiana 3
Ultimate Analysis (%, Dry)		
Carbon	68.5	73.0
Hydrogen	4.9	4.8
Nitrogen	1.45	1.3
Sulfur	2.5	1.3
Oxygen	12.05	9.0
Ash	10.6	10.6
Moisture (%)	4.5	3.2
Heating Value (Dry) Btu/lb	12,400	12,760
% Volatiles (Dry)	39.75	34.3
Forms of Sulfur (%, Dry)		
Total	2.6	1.3
Pyritic	0.55	0.58
Organic	1.18	0.47
Sulfate	0.87	0.24

2.5 to 1.3 percent. All of the coal-fired Series B tests used the Indiana 3 (1.3% S) coal. The sorbent used for all of the tests was vicron 45-3. Firing conditions for specific experiments are indicated in the discussion of the experiments. The small scale distributed mixing burner was used for all of the burner staged experiments. The divergent fuel injector was used for the coal (see Appendix B), and the axial gas injector was used for the gas.

6.1 Sulfur Chemistry and Thermal Environment Studies - Propane Fired (Series B-1)

The first set of thermal environment studies (propane fired) had two basic aspects: the further investigation of the gas phase sulfur chemistry under fuel-rich conditions and study of the impact of thermal environment and sorbent location on overall sorbent utilization without the complication of condensed fuel sulfur compounds and char burnout. Figure 6-1 shows the completed test matrix for the propane fired experiments. The experimental scheme evolved during the testing, reflecting a shift of emphasis as the most important parameters and most interesting conditions became clearer. This change in emphasis is indicated in the test matrix shown in Figure 6-1.

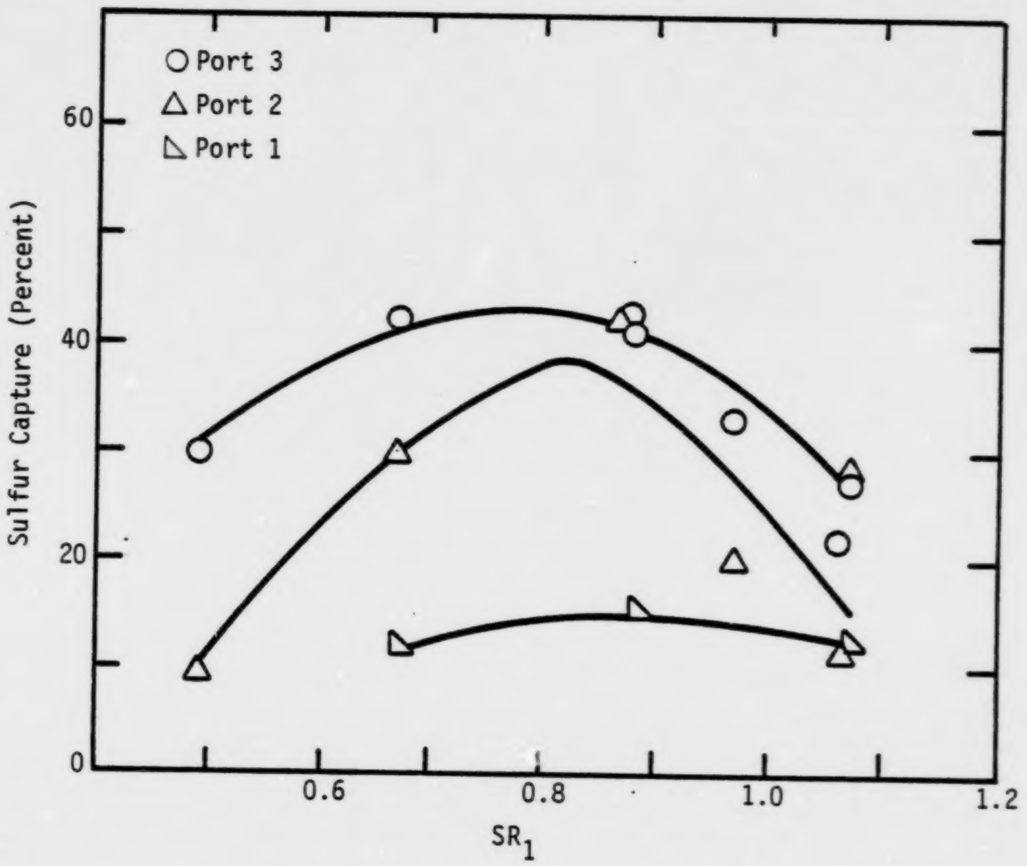
Overall sulfur capture through the furnace for three thermal conditions and three sorbent injection locations was determined as a function of first stage stoichiometry. Figure 6-2 shows the effect of first stage stoichiometry on sulfur capture at Port 2 (exit of post-flame cavity) and Port 3 (exit of convective sections). Note that the sulfur capture does not decrease as much at low first stage stoichiometries as when firing with coal. The data plotted in Figure 6-3 show the effect of first stage stoichiometry on sulfur capture throughout the furnace when the sorbent was injected at the base of the radiant furnace (air as the sorbent carrier). The sorbent transport air, which was 10 to 15 percent of the theoretical air, this air flow is included in the overall excess air (from 1.09 to 1.17 of theoretical) rather than in the first stage (SR_1) air. Overall sulfur capture was highest at first stage stoichiometries between 0.9 and 0.65 and dropped



Fuel: Propane + H_2S
Staging: External
Cooling: None
Sorbent Loc.: With Fuel
SO_2: ~2500 ppm

Load: 1.02-1.07
Run: 1-12,1-13,1-28
Ca/S: 1.7-2.3
Sorbent: $CaCO_3$ (Vicron 45-3)
SR_p: ~0.12
SR_T: 1.13-1.17

Figure 6-2. Effect of first stage stoichiometry on sulfur capture, uncooled, sorbent with fuel.



Fuel: H_2S + Propane
Staging: External
Cooling: None
Sorbent Loc.: Base of Rad. Furn.
SO_2: ~2500 ppm

Load: 0.96-1.10
Run: 1-8,12-11,12-12
Ca/S: 1.7-2.5
Sorbent: $CaCO_3$(Vicron 45-3)
SR_P: (Sorbent transport air 0.1-0.15)
SR_T: 1.09-1.17

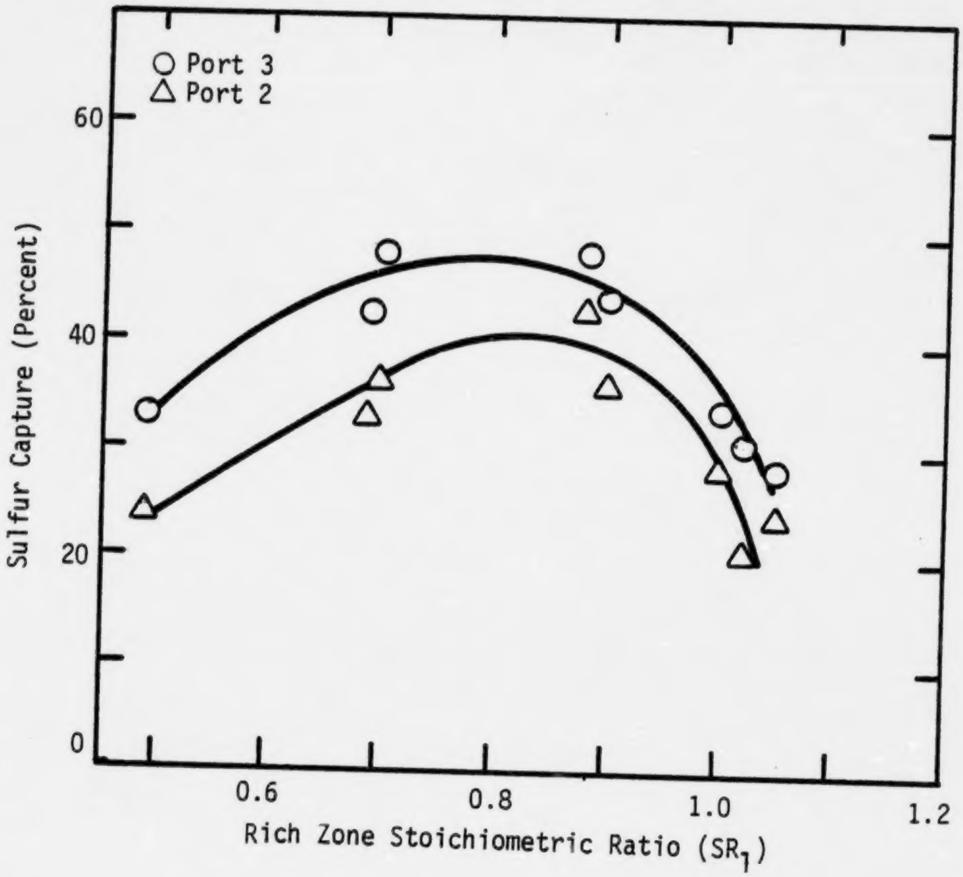
Figure 6-3. Effect of first stage stoichiometry on sulfur capture, H_2S doped propane, uncooled, sorbent ($CaCO_3$) at base of radiant furnace.

considerably at excess air ($SR_1 > 1.0$) conditions. The sulfur capture across the convective section was high at low first-stage stoichiometries, probably because the convective section was hot (entrance temperature > 2200°F).

The effect of first-stage stoichiometry on sulfur capture when the sorbent was added with the staging air is shown by the data plotted in Figure 6-4. Again sulfur capture is highest at first-stage stoichiometries between 0.65 and 0.9. The dropoff in capture under excess air conditions may be due to low sorbent injection velocities (because the staging air flow rate is low) or to low temperatures at the injection point. (Temperatures at the staging point are typically 1900-2100°F, which may not be high enough for calcination of the limestone).

The radiant section of the BSF was cooled and sorbent was added with the fuel at several first-stage stoichiometries (Figure 6-5). Similar data (cooling in the radiant furnace) for sorbent injection at the base of the radiant furnace was also collected (see Figure 6-6). Approximately 8 percent of the total heat input was extracted by the cooling coils. At low first-stage stoichiometries capture in the convective section was high probably because of the high entrance temperatures under staged conditions. The cooling pipes were then moved to the transition between the radiant and postflame section. The data plotted in Figure 6-7 show the effect of the first-stage stoichiometry for this cooling configuration. The sorbent was injected with the fuel. Under these conditions, sulfur capture did not drop off at low primary zone stoichiometries but was very low at excess air conditions.

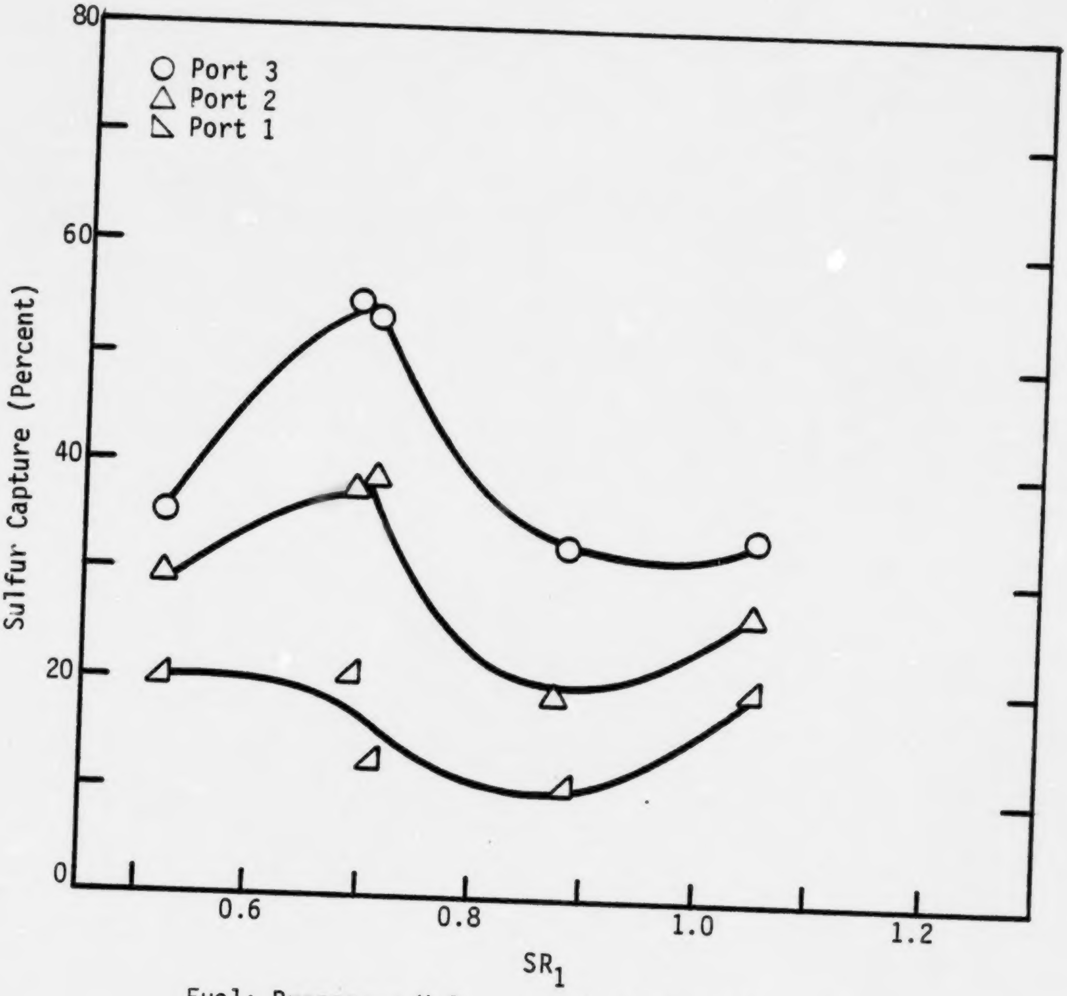
Figures 6-3 through 6-8 summarize data taken for test series B-1 in terms of sulfur capture through the furnace as a function of first stage stoichiometry. In order to discuss the effect of other parameters (such as cooling and sorbent location) the data has been reduced to terms of overall sorbent utilization. Utilization is defined as (SO_2 capture) ÷ (Ca/S mole ratio); for example 50 percent capture at a Ca/S mole ratio of two yields 25 percent sorbent utilization. The use of percent utilization rather than percent capture simplifies the comparison of data taken at different Ca/S mole ratios.



Fuel: Propane + H_2S
Staging: External
Cooling: None
Sorbent Loc.: Staging Air
SO_2: ~2500 ppm

Load: 1.04-1.14
Run: 1-19,1-21,1-22
Ca/S: 1.7-2.2
Sorbent: CaCO3(Vicron 45-3)
SR_P: ---
SR_T: 1.14-1.19

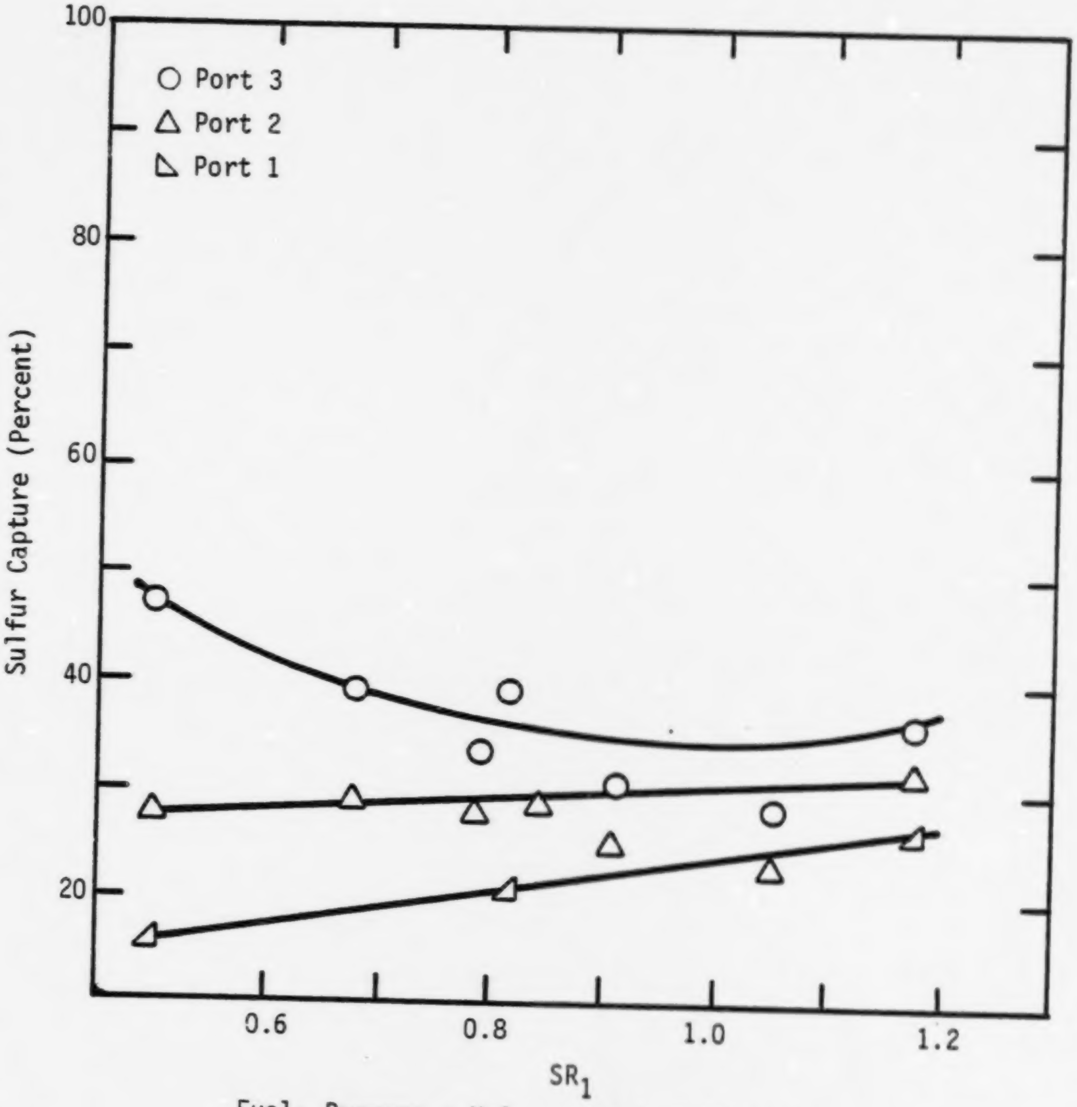
Figure 6-4. Effect of first stage stoichiometry on sulfur capture, H_2S doped propane, uncooled, sorbent ($CaCO_3$) with staging air.



Fuel: Propane + H_2S
Staging: External
Cooling: Radiant Furn.
Sorbent Loc.: With Fuel
SO_2: 2500 ppm

Load: 0.99-1.10
Run: 12-17,12-19
Ca/S: 2.0-2.3
Sorbent: $CaCO_3$(Vicron 45-3)
SR_P: 0.12
SR_T: 1.11-1.21

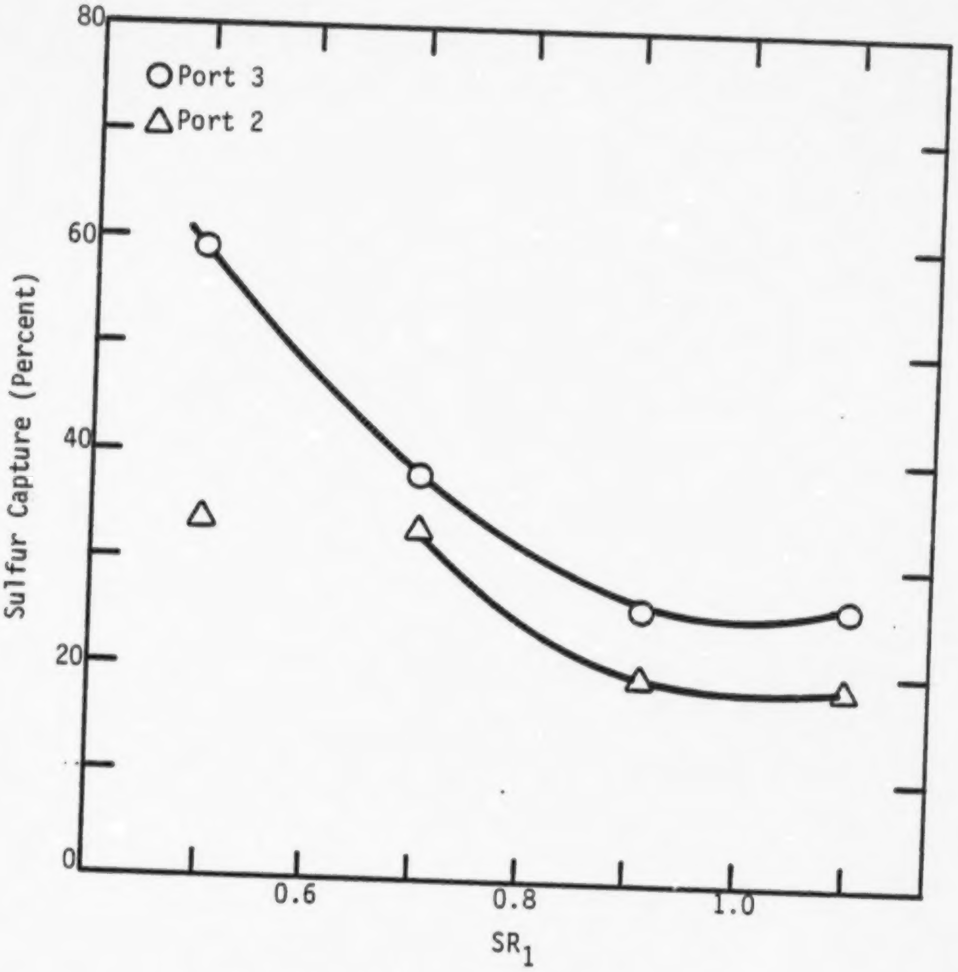
Figure 6-5. Effect of rich zone stoichiometry on sulfur capture, cooled propane + H_2S, sorbent with fuel.



Fuel: Propane + H_2S
Staging: External
Cooling: Radiant Fur.
Sorbent Loc.: Base of Radiant Fur.
SO_2: 2500 ppm

Load: 0.99-1.07
Run: 12-15,12-16
Ca/S: 2.0-2.5
Sorbent: $CaCO_3$, (Vicron 45-3)
SR_P: (Sorbent transport air 0.1-0.15)
SR_T: 1.13-1.22

Figure 6-6. Effect of rich zone stoichiometry on capture, cooled, sorbent injected at the base of the radiant furnace.



Fuel: Propane + H_2S
Staging: External
Cooling: Hor. Trans.
Sorbent Loc.: With Fuel
SO_2: ~2500 ppm

Load: 1.02-1.07
Run: 2-2
Ca/S: 2.2-2.5
Sorbent: $CaCO_3$(Vicron 45-3)
SR_P: ---
SR_T: 1.10-1.18

Figure 6-7. Effect of first stage stoichiometry on sulfur capture, cooling in horizontal transition. Propane + H_2S, sorbent with fuel.

Sulfur capture as a function of first-stage stoichiometry for several sorbent injection and cooling locations was measured in Series B-1. Comparison of the data is complicated by the fact that changing the first-stage stoichiometry affects more than just the first zone chemistry. The effects of changing first-stage stoichiometry on various parameters of the propane H_2S fired system are summarized in Figure 6-8. The furnace cooling was in the radiant section, the SO_2 level at the exit was ∿1500 ppm, and the sorbent was added with the fuel. Reducing the first-stage stoichiometry reduces the bulk gas temperature in the first stage and increases the bulk gas temperature after the staging point because more of the fuel heat release takes place in the second stage. The temperature at the entrance to the convective section increases (see Figure 6-8c). Reducing the first-stage stoichiometry reduces the total mass flow rate through the radiant furnace (the first stage) and therefore increases the total first stage residence time as shown in Figure 6-8b. The effect of first-stage stoichiometry on sorbent utilization at the exit of the post-flame cavity (Port 2) and the exit of the convective sections (Port 3) is shown in Figure 6-8a.

The data plotted in Figure 6-9 shows the effect of cooling in the radiant zone on gas temperatures and overall sorbent utilizations. Two phenomena should be noted: 1) the cooling coils in the radiant section extracted more heat (ΔT of $\sim 700^\circ F$) at excess air conditions than at highly staged conditions. This was due to the lower flame temperatures at low SR_1's and to soot depositing on the coils under fuel-rich conditions, and 2) at excess air conditions cooling slightly decreased sorbent utilization but had little effect under highly staged conditions. (Gas temperatures were measured at the exit of the radiant furnace (first stage temperature) and at sample Port #1, just after the staging air addition location (second-stage temperature).

The effect of cooling the radiant furnace on sorbent utilization for a range of first-stage stoichiometries was assessed (Figure 6-10. The sorbent was injected with air at the base of the radiant furnace. Again cooling was dependent on the first-stage stoichiometry and had either little or a detrimental effect on sorbent utilization. It is not clear why sorbent utilization peaks at first-stage stoichiometries between 0.6 and 0.9 for uncooled conditions and is very nearly independent of SR_1 for cooled conditions.

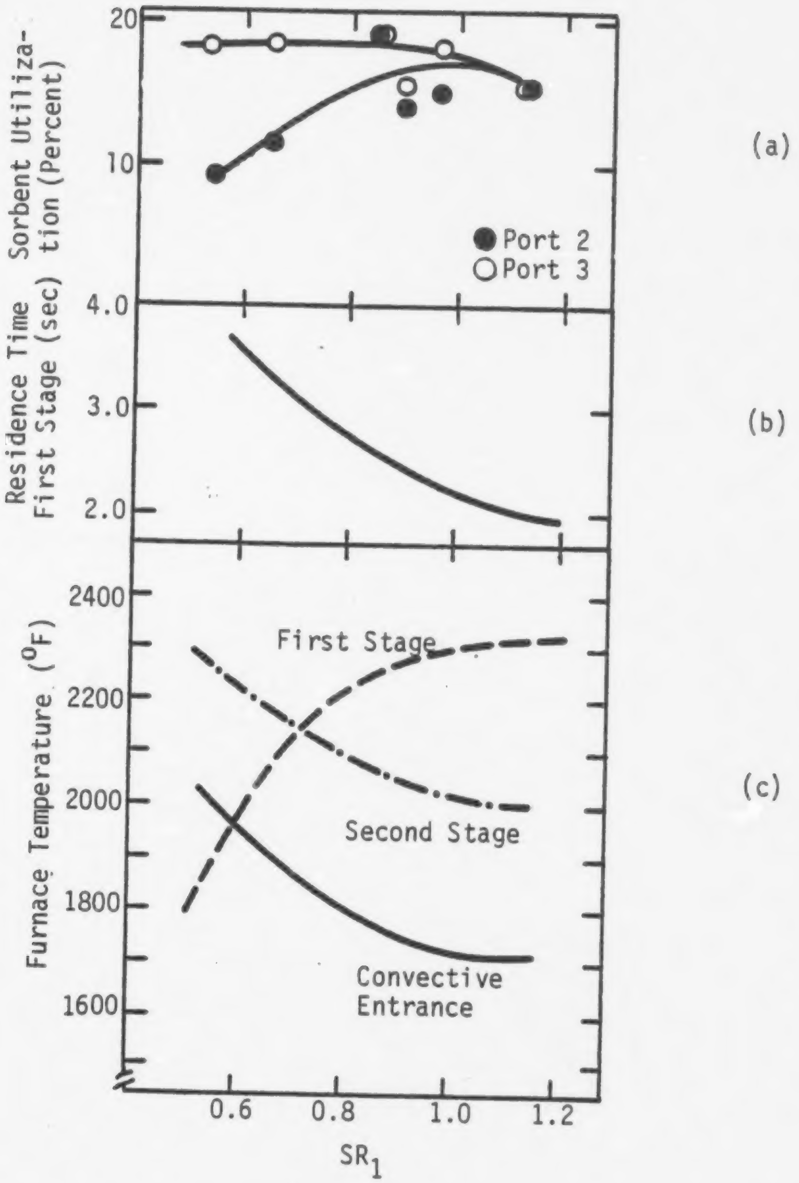


Figure 6-8. Effect of first stage stoichiometry on sorbent utilization and thermal history.

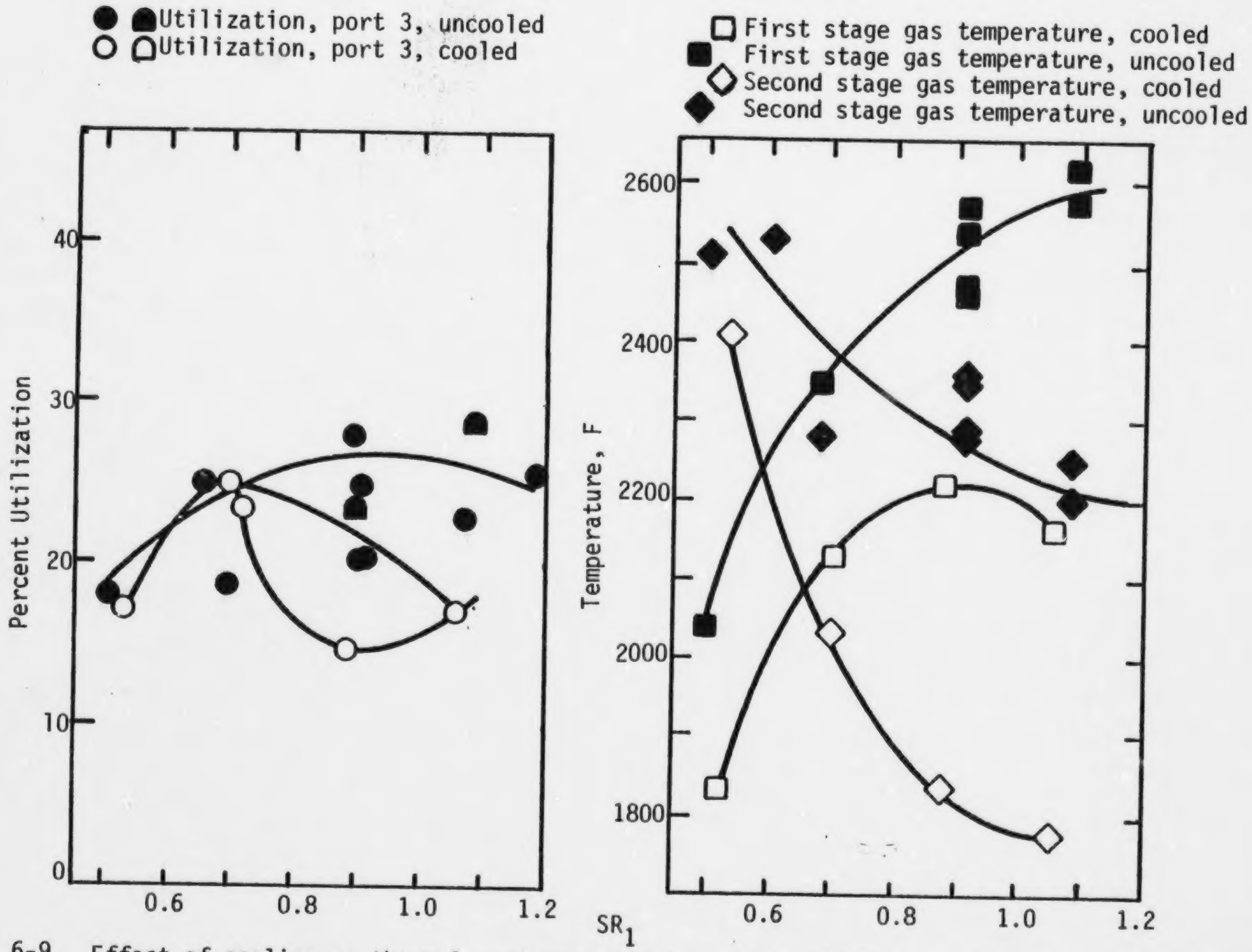


Figure 6-9. Effect of cooling on thermal environment and sorbent utilization, sorbent added with propane (propane + H_2S).

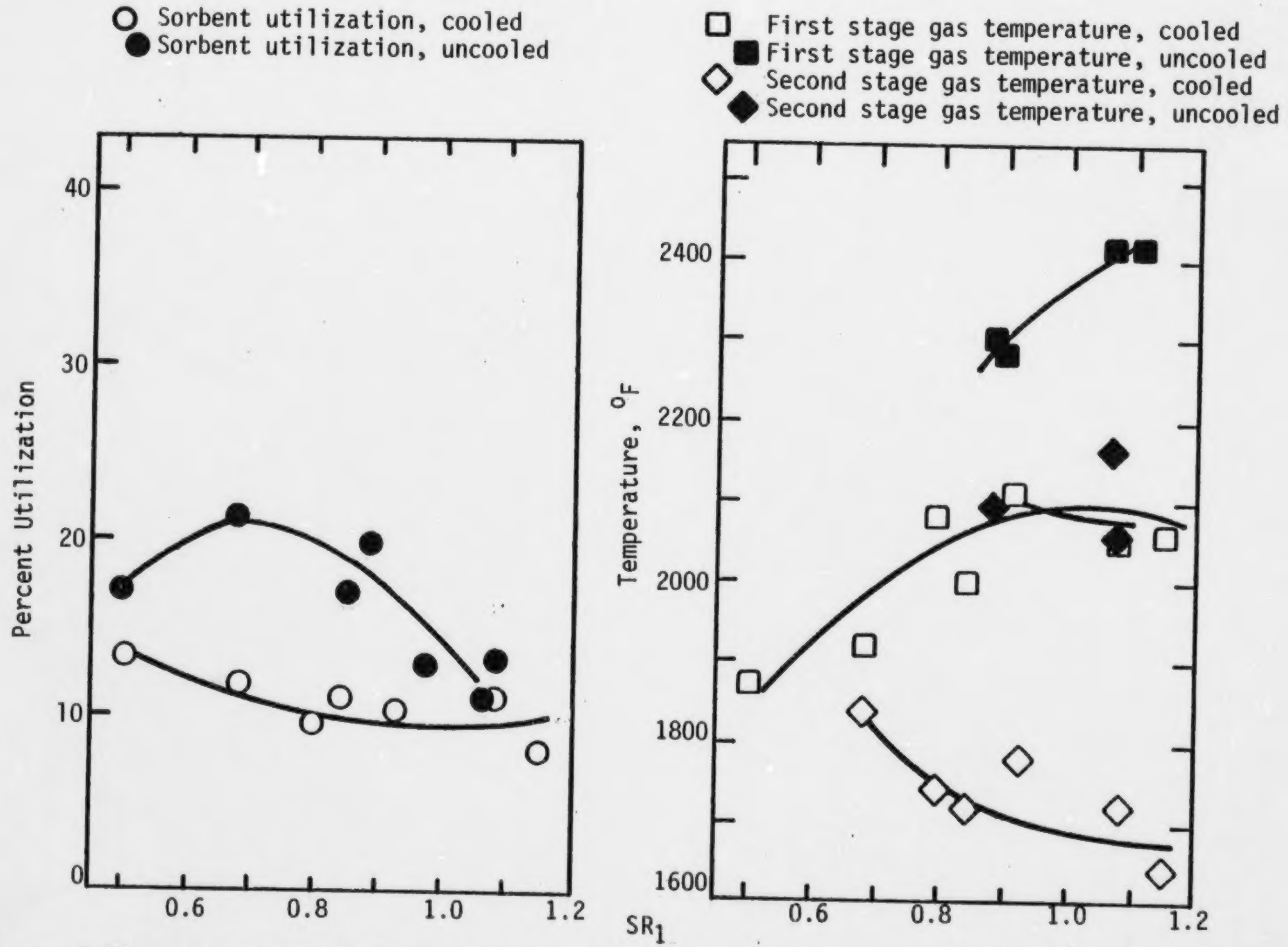


Figure 6-10. Effect of cooling on thermal environment and sorbent utilization, sorbent at base of radiant furnace.

Figure 6-11 shows the effect of cooling location on gas temperatures and sorbent utilization for a number of first-stage stoichiometries. Sorbent was added with the fuel. The cooling location had little effect on the second-stage temperature. Cooling the horizontal transition gave slightly lower first-stage temperatures than cooling in the radiant furnace did. Cooling the horizontal transition increased sorbent utilization at low ($SR_1 = 0.5$) first stage stoichiometries over both the cooled in the radiant zone and uncooled conditions.

Under excess air conditions sorbent injection with the fuel gave better sorbent utilization than injection in the staging air or at the base of the radiant furnace. (see the data summarized in Figure 6-12 showing the effect of sorbent location on sorbent utilization as a function of first stage stoichiometry). At highly staged conditions ($SR_1 = 0.5$) injection location had no effect on sorbent utilization.

During the experiments discussed above batch samples were taken from the first stage in order to investigate the effect of stoichiometry and thermal environment on sulfur species distribution in the gaseous flame. The samples were analyzed using the gas chromatograph/flame photometric defector system. The rich zone sulfur species distributions measured for cooled and uncooled conditions are summarized in Figure 6-13. A comparison of the measured species distribution with equilibrium calculations (see Figure 6-13a) indicates that even for gaseous fuels the sulfur species under fuel-rich conditions are nonequilibrium.

6.2 Sulfur Chemistry and Thermal Environment--Coal Fired (Series B-2)

The effect of thermal environment on sulfur capture from the coal flame was further investigated. In the experiments discussed in this section thermal environment was altered by altering firing conditions rather than by cooling the furnace. Two sets of experiments were performed using the two basic staging systems: a) internal (burner) staging, and b) external (physical) staging. The effect of air heat, flue gas recirculation (FGR) simulated by dilution with nitrogen, and sorbent location were investigated. Figure 6-14 shows the completed test matrix for the coal-fired thermal environment studies.

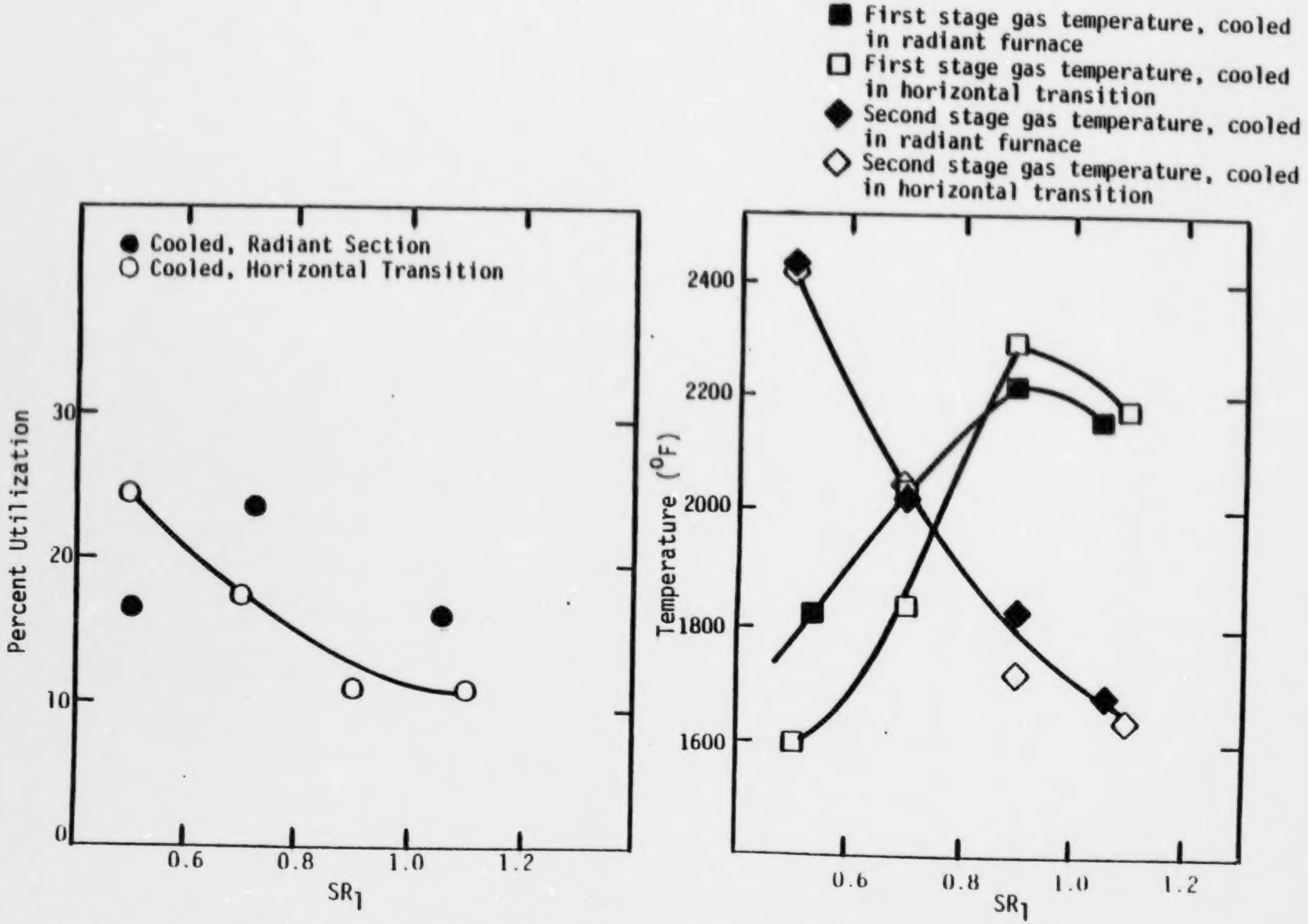


Figure 6-11. Effect of cooling location on sorbent utilization and thermal history, propane fired, sorbent with fuel.

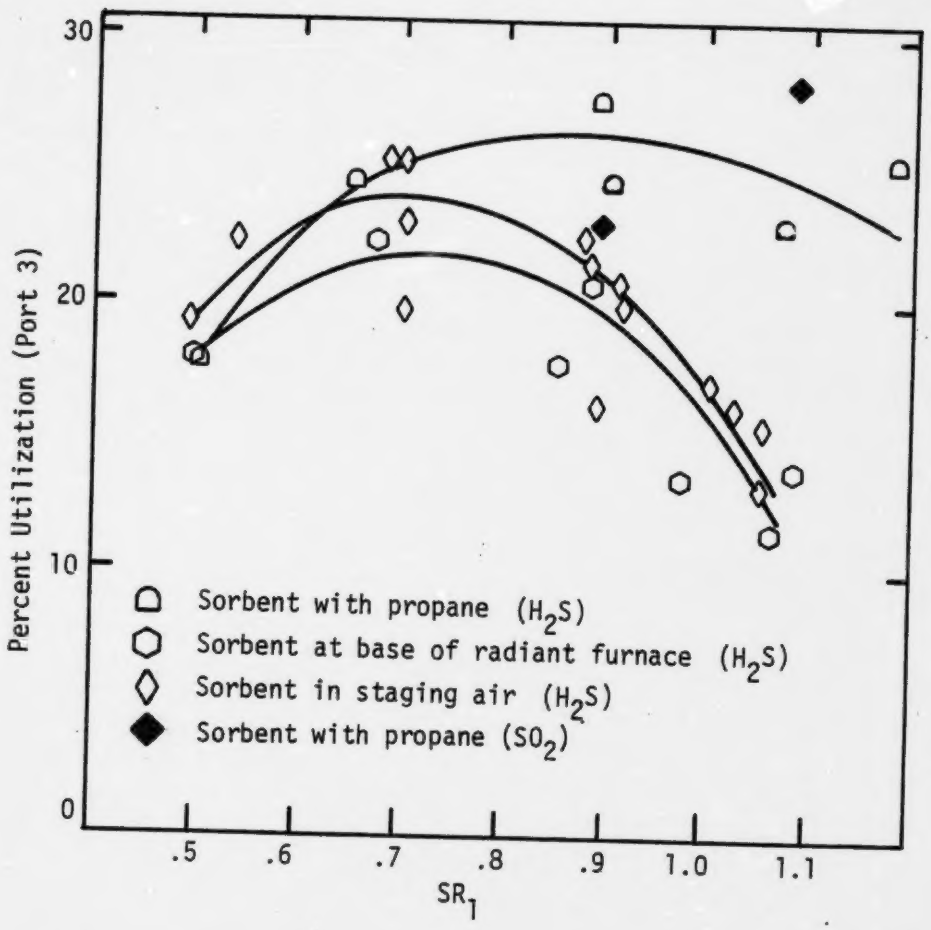
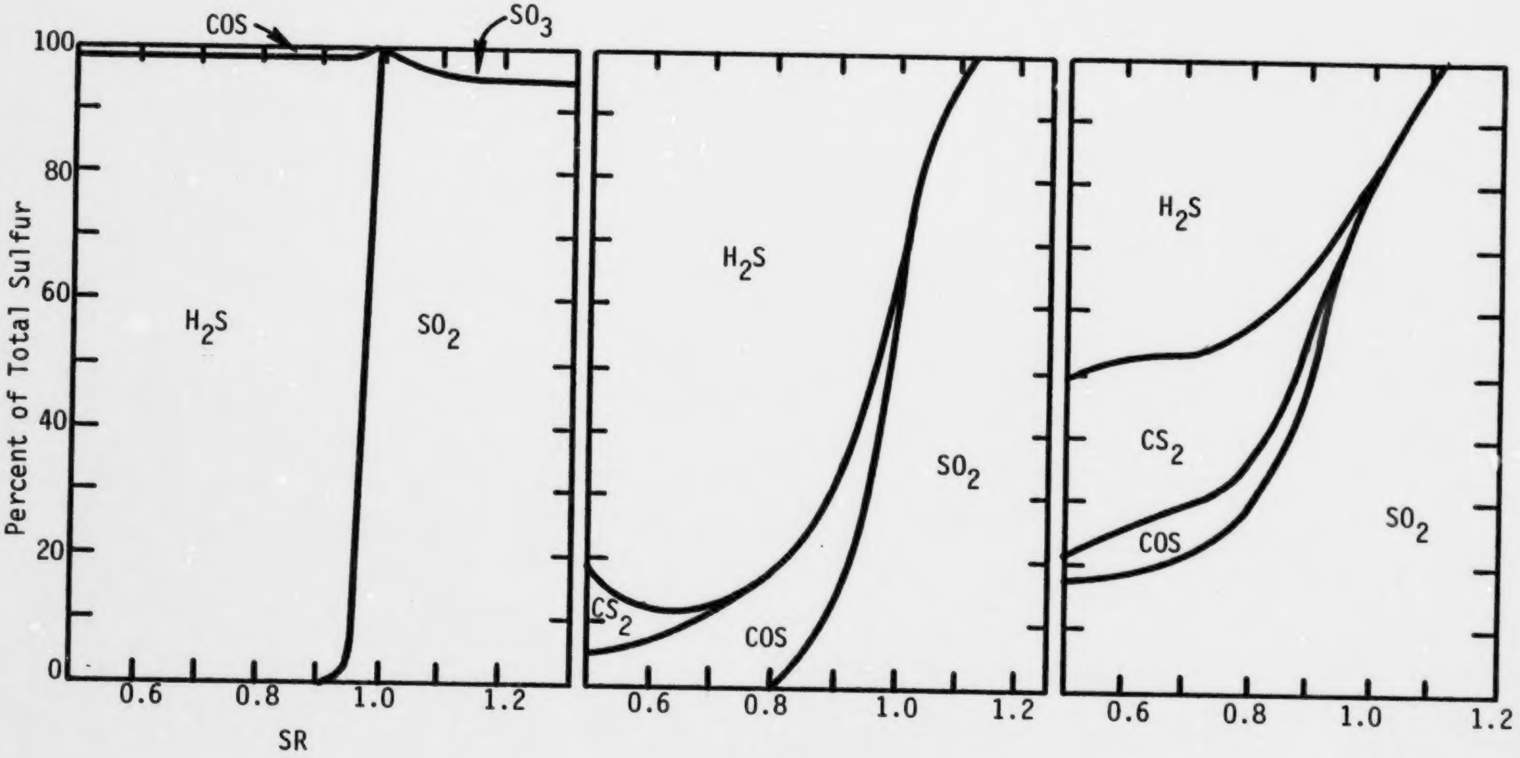


Figure 6-12. Comparison of overall sorbent utilization for various injection locations, H_2S or SO_2 doped propane, uncooled, Vicron 45-3 ($CaCO_3$) sorbent.



(a) Equilibrium

(b) Propane/H_2S, Uncooled)

(c) Propane/H_2S, Cooled

Figure 6-13. Comparison of equilibrium and measured sulfur species distribution.

	Internally Staged								Externally Staged							
	Sorbent with Coal				Sorbent in T.A.				Sorbent with Coal				Sorbent in S.A.			
	1.1	0.9	0.7	0.5	1.1	0.9	0.7	0.5	1.1	0.9	0.7	0.5	1.1	0.9	0.7	0.5
Maximum Air Heat	3-5	3-5	3-5	3-5					2-17	2-17	2-17	2-17	2-18	2-18	2-18	2-18
N_2 Dilution All Air	2-23	2-23	2-23	2-23	2-25	2-25	2-25		2-26	2-26	2-26		2-27	2-27	2-27	
Radiant Cooling Top of Furnace																
Radiant Cooling Bottom of Furnace																
N_2 Dilution Staging Air									3-4	3-4	3-4	3-4				
N_2 Dilution Staging Air + Maximum Preheat									3-4	3-4	3-4	3-4				

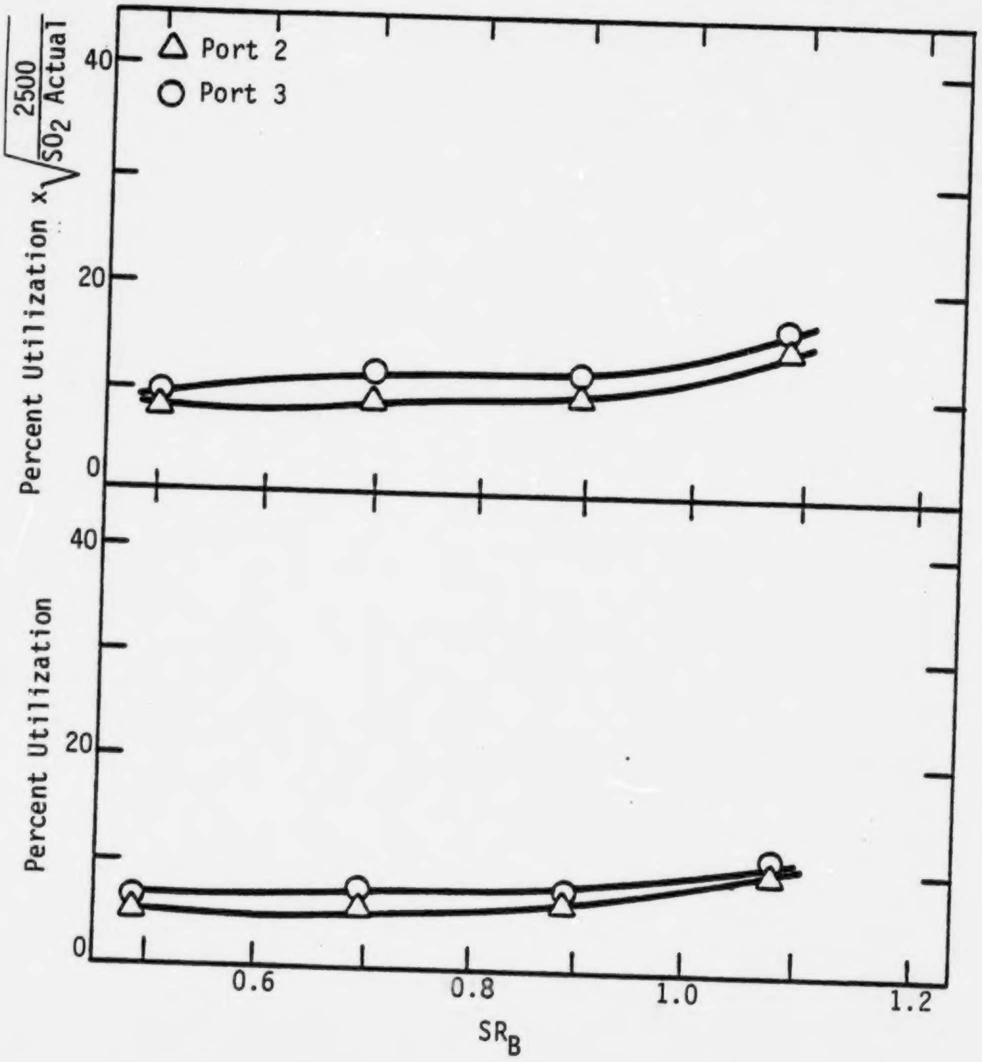
Figure 6-14. Test matrix, coal fired, thermal environment studies.

The first set of experiments were performed under internally staged conditions. Fuel was conveyed with primary air and injected through a divergent nozzle into the furnace. Secondary air was added annularly and tertiary or staging air was added through four outboard staging air ports located in the firing wall between the quarl and the furnace wall (see Figure 6-1).

The data plotted in Figure 6-15 show the effect of burner zone stoichiometry on sorbent utilization using burner staging and air preheat. The sorbent was added with the fuel. Figure 6-15 shows the data obtained plotted simply as a function of SR_1 and also as utilization multiplied by $\sqrt{2500/SO_2 \text{ Actual}}$ to allow comparison with data taken using the higher sulfur Indiana 2 coal. It is clear that, as observed in the earliest tests, sulfur capture (and sorbent utilization) are poor for the uncooled, internally staged conditions.

Flue gas recirculation (FGR) was simulated by diluting the combustion air by 20 percent with nitrogen. The FGR improved capture only slightly over the uncooled conditions (Figure 6-16), possibly because enhancement of the sulfur capture due to reduced peak flame temperatures was counteracted by the overall shorter residence time in the furnace and the lower driving force (due to the N_2 dilution). With both these cases (air preheat and N_2 dilution) the sorbent was added with the fuel and burner zone stoichiometry had only a small impact on sorbent utilization. The data shown in Figure 6-17 indicate the effect of burner zone stoichiometry on sulfur capture when the sorbent was injected with the staging air under simulated FGR conditions. The sulfur capture was lower than when the sorbent was added with the fuel, especially under unstaged conditions.

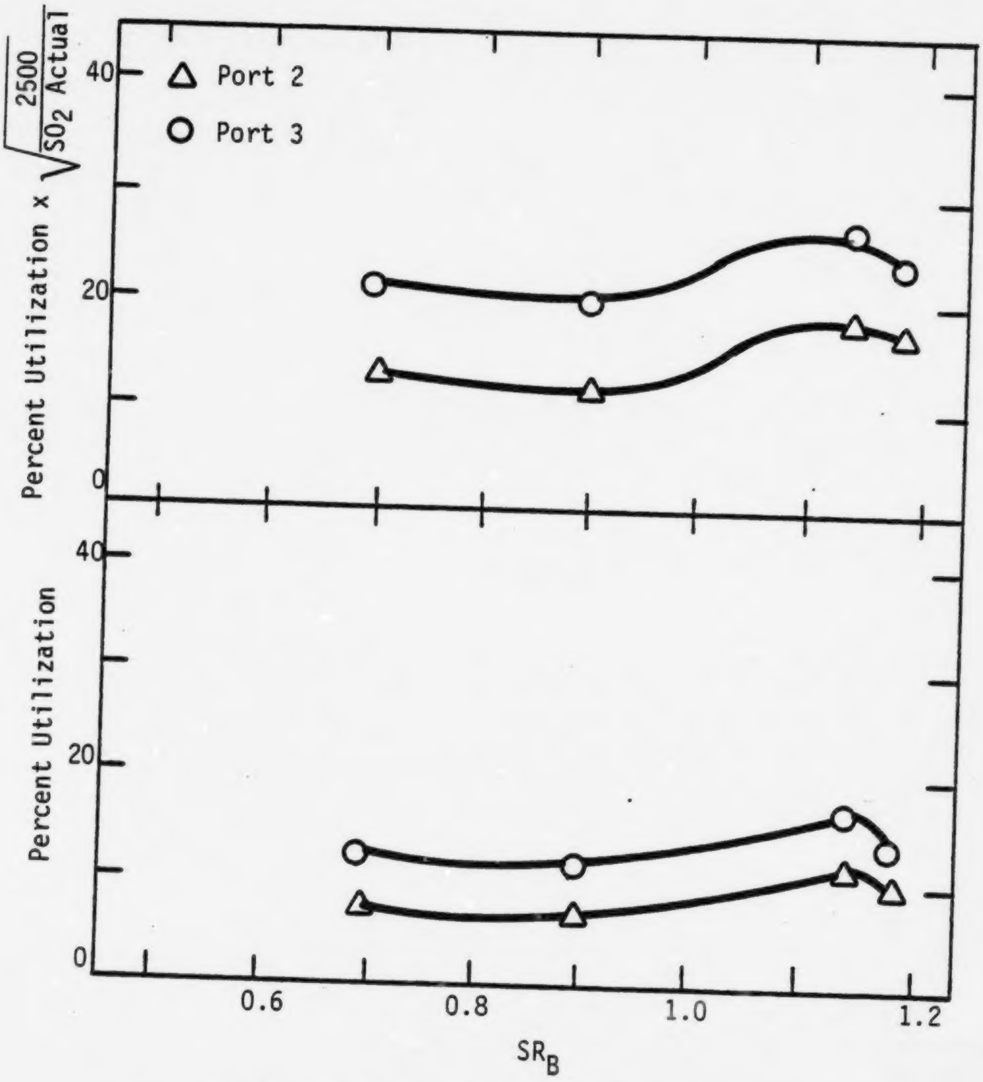
The second batch of experiments were done under external, or physically staged conditions; the staging air was added at the base of the postflame section and the entire radiant furnace operated fuel rich. Figure 6-18 shows the data obtained at various first-stage stoichiometries with secondary air preheat and the sorbent added with the fuel. As was seen in earlier experiments, sulfur capture decreased at low first-stage stoichiometries. The effect of first-stage stoichiometry on sulfur capture with air preheat and the sorbent added with the staging air is shown by the data in Figure 6-19.



Fuel: Indiana 3 Coal
Staging: Internal
Air Preheat: 420-450
Sorbent Loc.: With Fuel
N_2 Dilution: None

Load: 1.0 - 1.04
Run: 3-5
Ca/S: 1.6-1.7
Sorbent: $CaCO_3$ (Vicron 45-3)
SR_P: 0.2
SR_T: 1.16-1.19

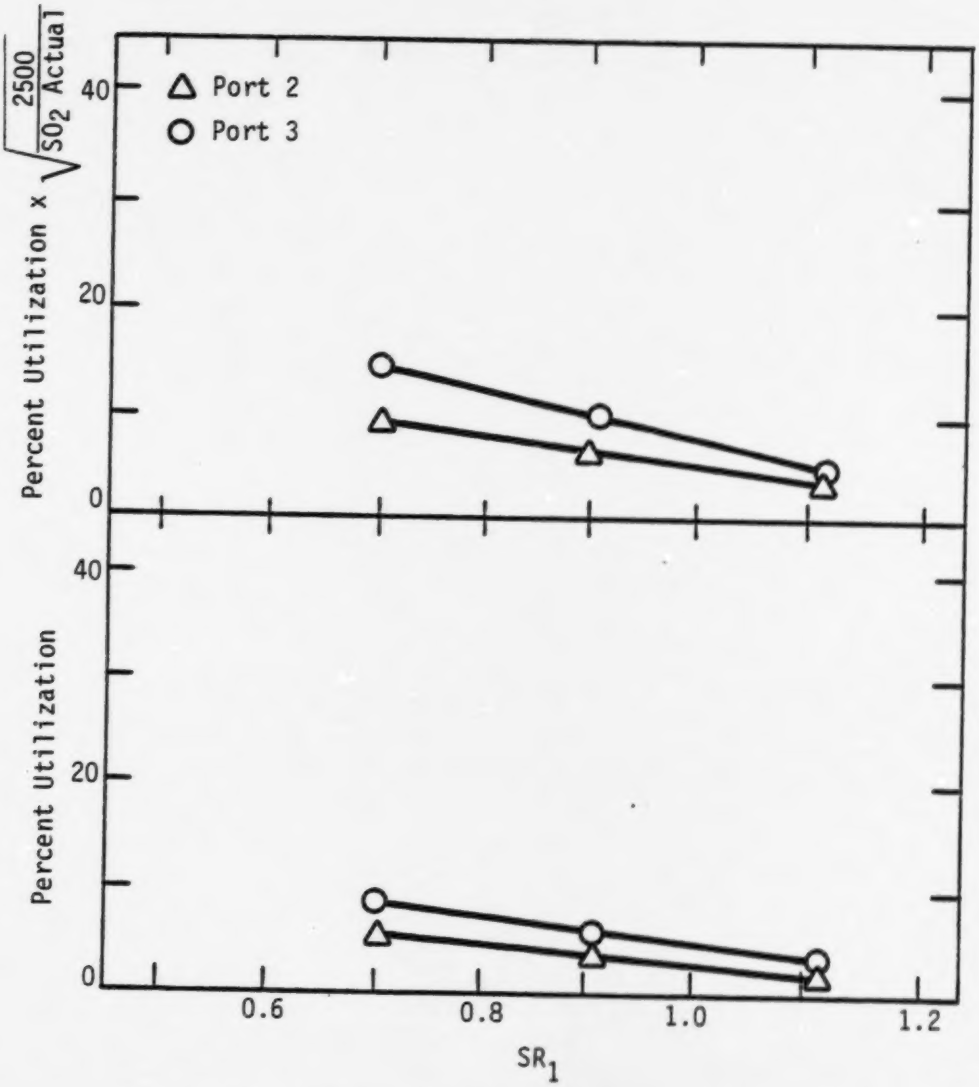
Figure 6-15. Effect of burner zone stoichiometry on sorbent utilization; high air heat.



Fuel: Indiana 3 Coal
Staging: Internal
Air Preheat: None
Sorbent Loc.: With Fuel
N_2 Dilution: 20% All Air

Load: 1.0-1.05
Run: 2-23
Ca/S: 1.9-2.0
Sorbent: $CaCO_3$ (Vicron 45-3)
SR_P: 0.18
SR_T: 1.23-1.30

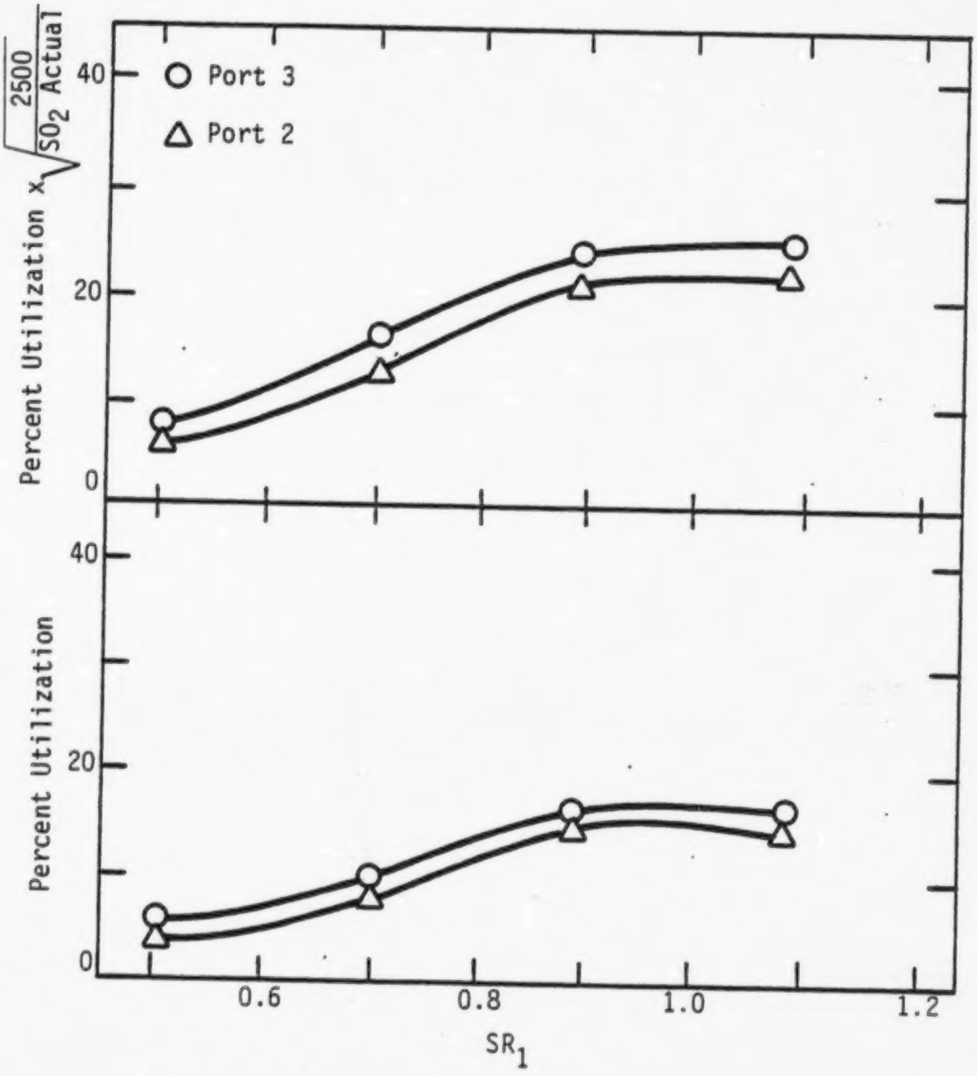
Figure 6-16. Effect of burner zone stoichiometry on sorbent utilization; nitrogen dilution, sorbent with fuel.



Fuel: Indiana 3 Coal
Staging: Internal
Air Preheat: None
Sorbent Loc.: Ter. Air
N_2 Dilution: 20% All Air

Load: 1.01-1.11
Run: 2-25
Ca/S: 1.7-1.9
Sorbent: $CaCO_3$(Vicron 45-3)
SR_P: 0.17-0.19
SR_T: 1.25-1.27

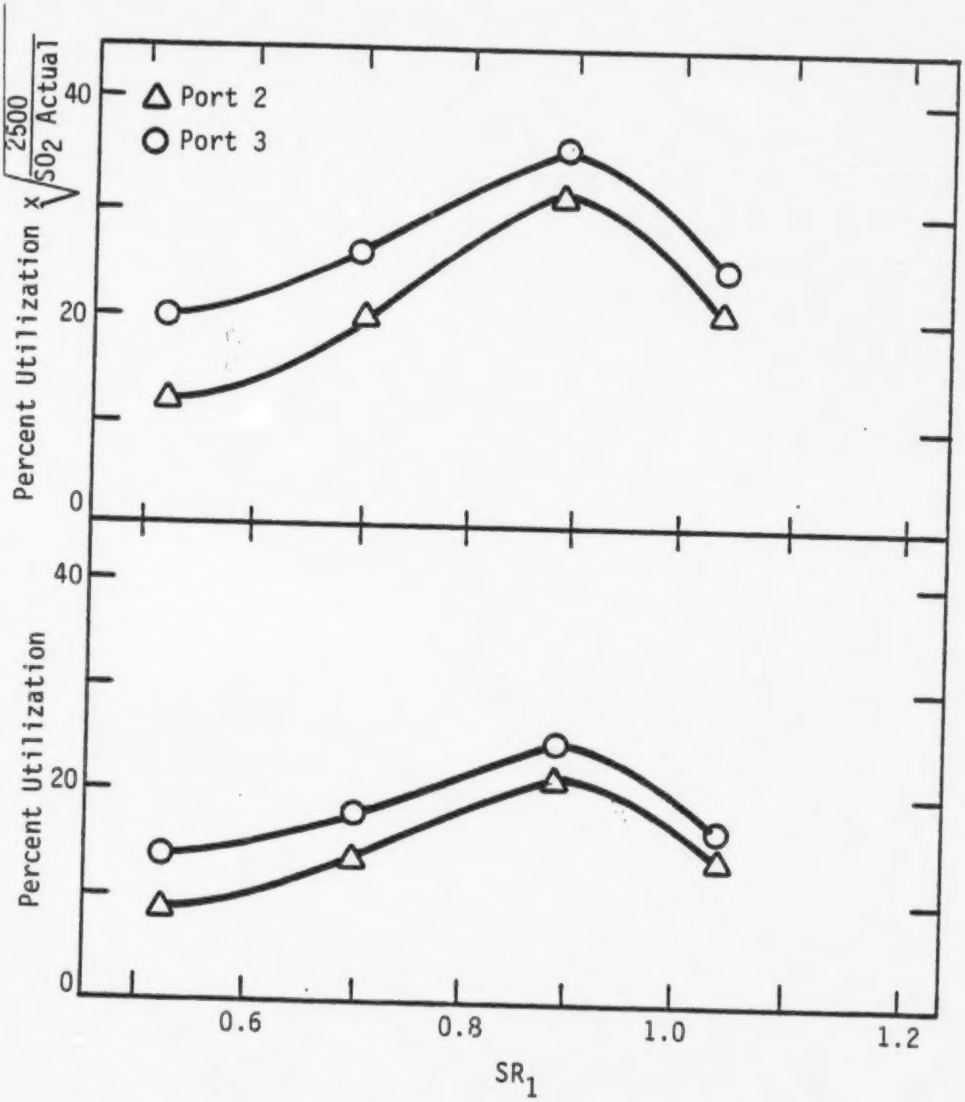
Figure 6-17. Effect of burner zone stoichiometry on sorbent utilization; nitrogen dilution sorbent with tertiary air.



Fuel: Indiana 3 Coal
Staging: External
Air Preheat: 400-490 F
Sorbent Loc.: With Fuel
N_2 Dilution: None

Load: 0.99-1.05
Run: 2-17
Ca/S: 1.6-1.9
Sorbent: $CaCO_3$(Vicron 45-3)
SR_P: 0.18-0.20
SR_T: 1.17-1.21

Figure 6-18. Effect of first stage stoichiometry on sorbent utilization; high air heat, sorbent with fuel.



Fuel: Indiana 3 Coal
Staging: External
Air Preheat: 390-460 F
Sorbent Loc.: Stag. Air
N_2 Dilution: None

Load: 1.0-1.08
Run: 2-18
Ca/S: 1.7-1.8
Sorbent: $CaCO_3$(Vicron 45-3)
SR_P: 0.20-0.21
SR_T: 1.17-1.19

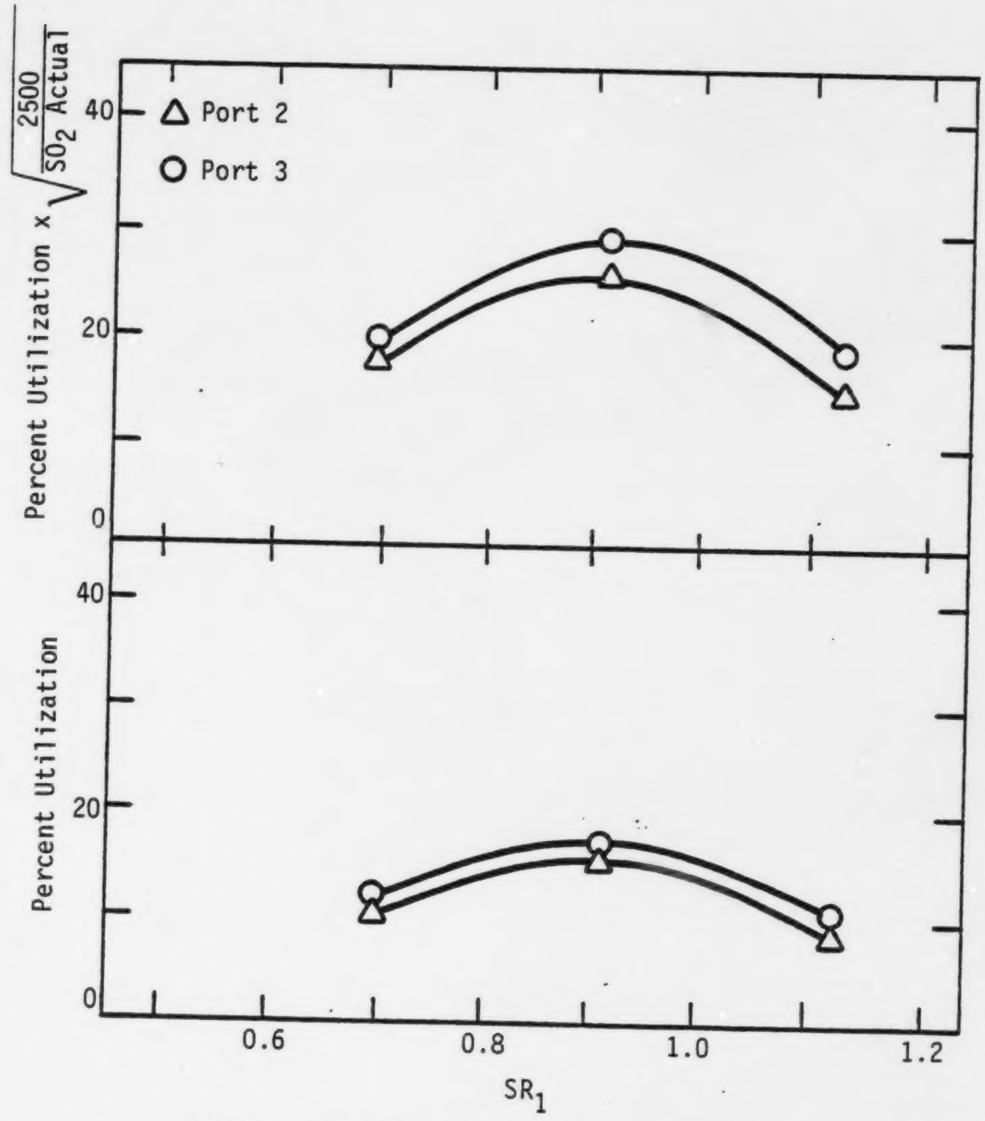
Figure 6-19. Effect of first stage stoichiometry on sorbent utilization; high air heat, sorbent with staging air.

Sorbent utilization peaks at stoichiometries around 0.9. This peak in utilization appears to be more pronounced with the air preheat than without.

The data shown in Figure 6-20 indicate the effect of first stage stoichiometry on sorbent utilization for simulated FGR conditions with the sorbent in the fuel. Sulfur capture is about the same as with air preheat; again, perhaps, because two opposing trends are at work; lower flame temperature which should enhance sulfur capture and decreased residence time and SO_2 concentration which will reduce sulfur capture. The effect of first-stage stoichiometry on sorbent utilization for simulated FGR conditions when the sorbent was added with the staging air is shown by the data in Figure 6-21. As seen before, sorbent utilization appears to peak when the sorbent is added to the staging air. The stoichiometry at which peak sorbent utilization occurred was slightly lower for the simulated FGR conditions than for the air preheat conditions. This is probably due to the difference in overall sorbent thermal history for the two firing schemes. Actual SR_1 at the sorbent injection location is probably less significant than cumulative thermal history of the sorbent-sulfur combination. The effect of first-stage stoichiometry on sorbent utilization for simulated FGR in the staging air is summarized by the data in Figure 6-22. Sorbent was added with the fuel and the secondary air was preheated. It was thought that dilution of the staging air would improve sulfur capture, especially at low first-stage stoichiometries, but it did not.

The effect of several thermal environments on the utilization of sorbent, added with the fuel, in the physically staged system is summarized by the data plotted in Figure 6-23. Simulated flue gas recirculation in all the combustion air gave the best sorbent utilization, although this was only slightly better than the air preheat conditions.

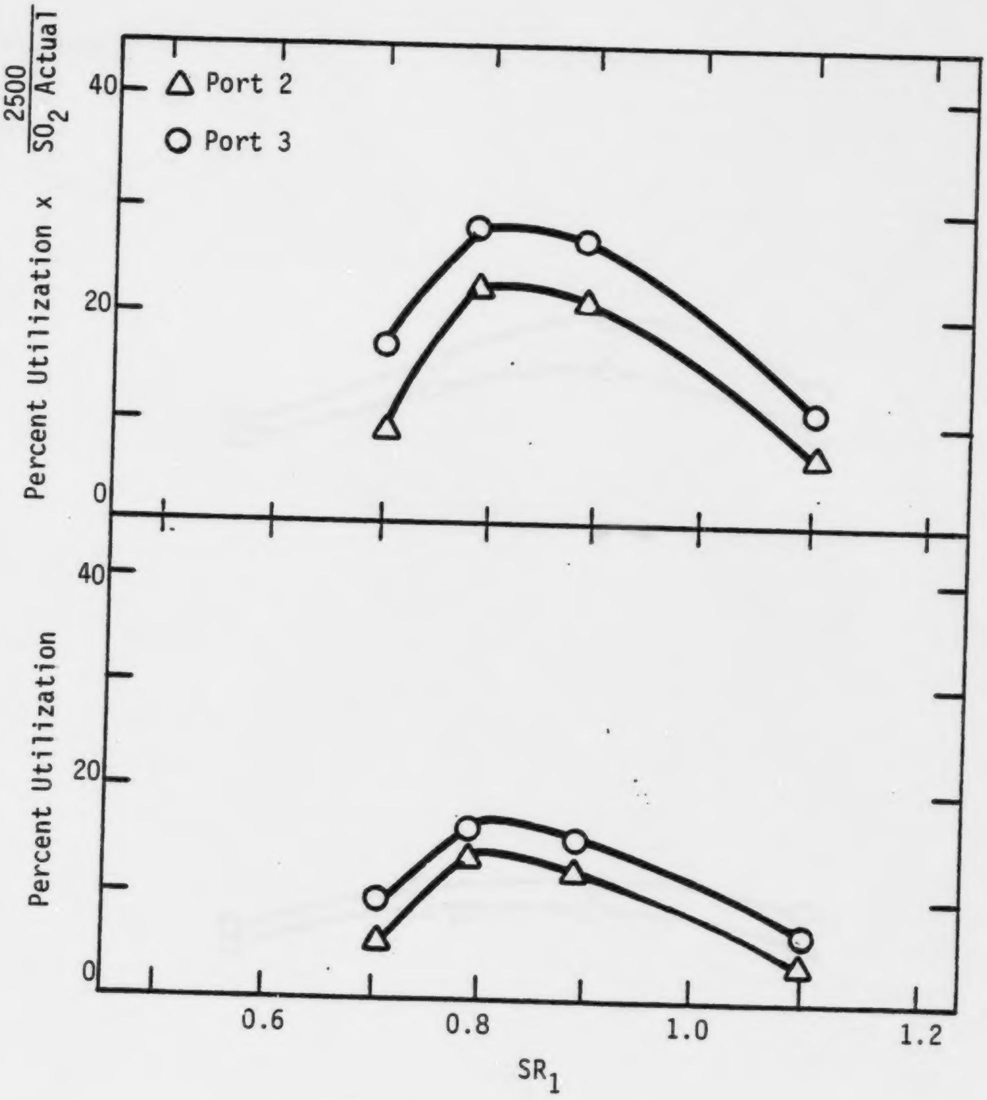
The effect of air heat and nitrogen dilution at several stoichiometries on sorbent utilization when the sorbent was added with the (external) staging air is summarized by the data in Figure 6-24. Under these conditions high air heat in the first stage gave better capture than FGR (N_2 dilution). In fact, this scheme gave the best overall sorbent utilization of all the externally staged, coal-fired conditions investigated.



Fuel: Indiana 3 Coal
Staging: External
Air Preheat: None
Sorbent Loc.: With Fuel
N_2 Dilution: 20% All Air

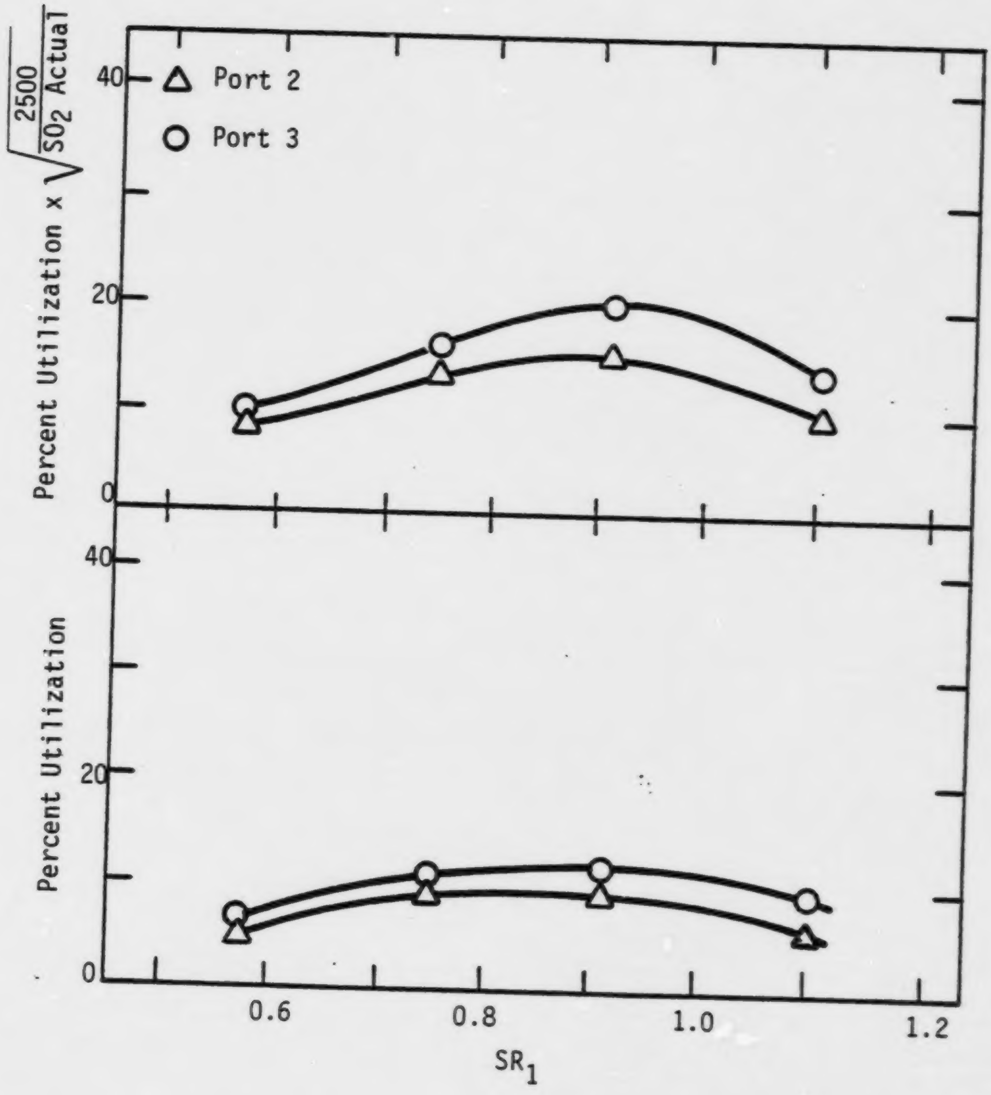
Load: 1.0-1.03
Run: 2-26
Ca/S: 1.9-2.0
Sorbent: $CaCO_3$(Vicron 45-3)
SR_p: 0.17-0.18
SR_T: 1.23-1.28

Figure 6-20. Effect of first stage stoichiometry on sorbent utilization; nitrogen dilution, sorbent with fuel.



Fuel: Indiana 3 Coal	Load: 1.01-1.06
Staging: External	Run: 2-27
Air Preheat: None	Ca/S: 1.8-1.9
Sorbent Loc.:Stag. Air	Sorbent: $CaCO_3$(Vicron 45-3)
N_2 Dilution:20% All Air	SR_P:0.18-0.19
	SR_T:1.23-1.28

Figure 6-21. Effect of first stage stoichiometry on sorbent utilization; nitrogen dilution, sorbent in staging air.



Fuel: Indiana 3 Coal	Load: 1.0-1.03
Staging: External	Run: 3-4
Air Preheat: 400-450 F	Ca/S: 1.7-1.9
Sorbent Loc.: With Fuel	Sorbent: $CaCO_3$(Vicron 45-3)
N_2 Dilution: 20% in Staging Air	SR_P: 0.18-0.2
	SR_T: 1.16-1.19

Figure 6-22. Effect of first stage stoichiometry on sorbent utilization; air heat and nitrogen dilution in staging air, sorbent with fuel.

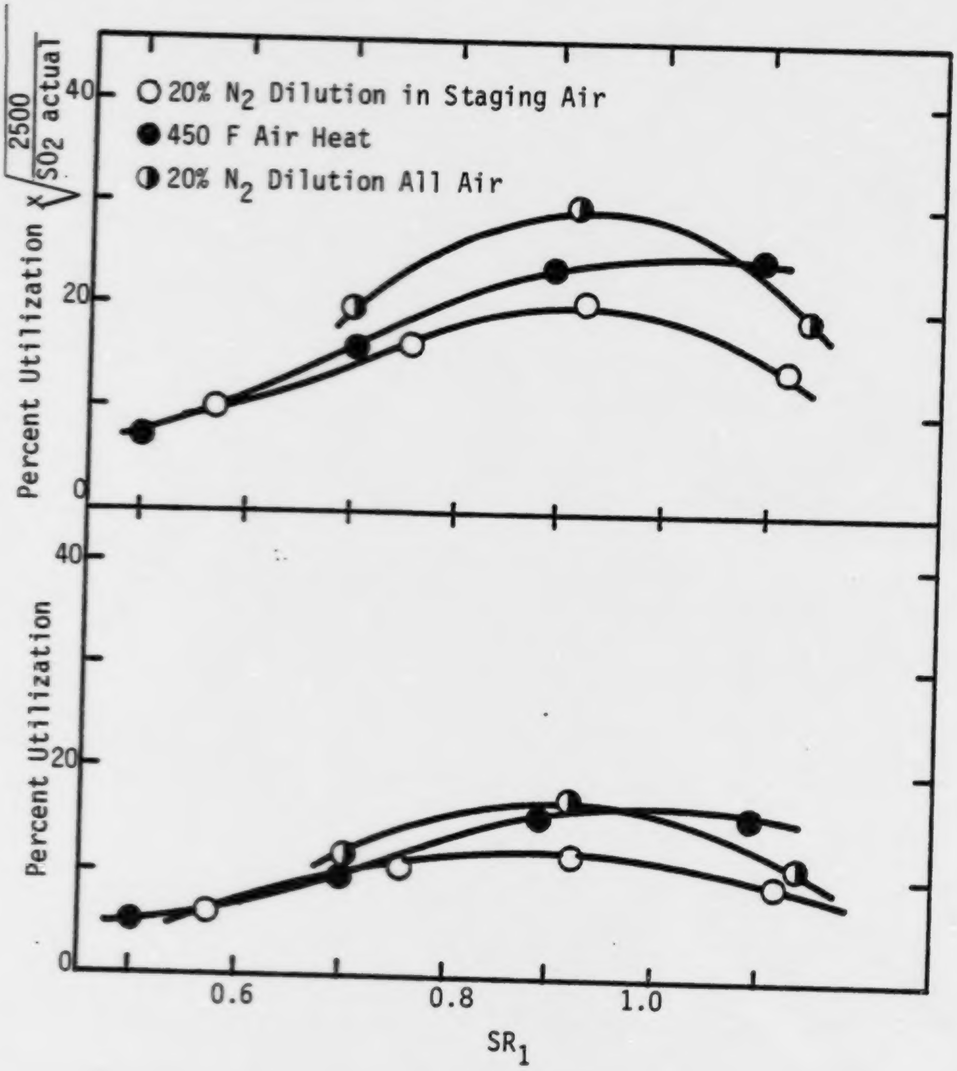


Figure 6-23. Effect of first stage stoichiometry on sulfur capture, three thermal environments, sorbent with fuel. Conditions as in 6-18, 6-20, 6-22.

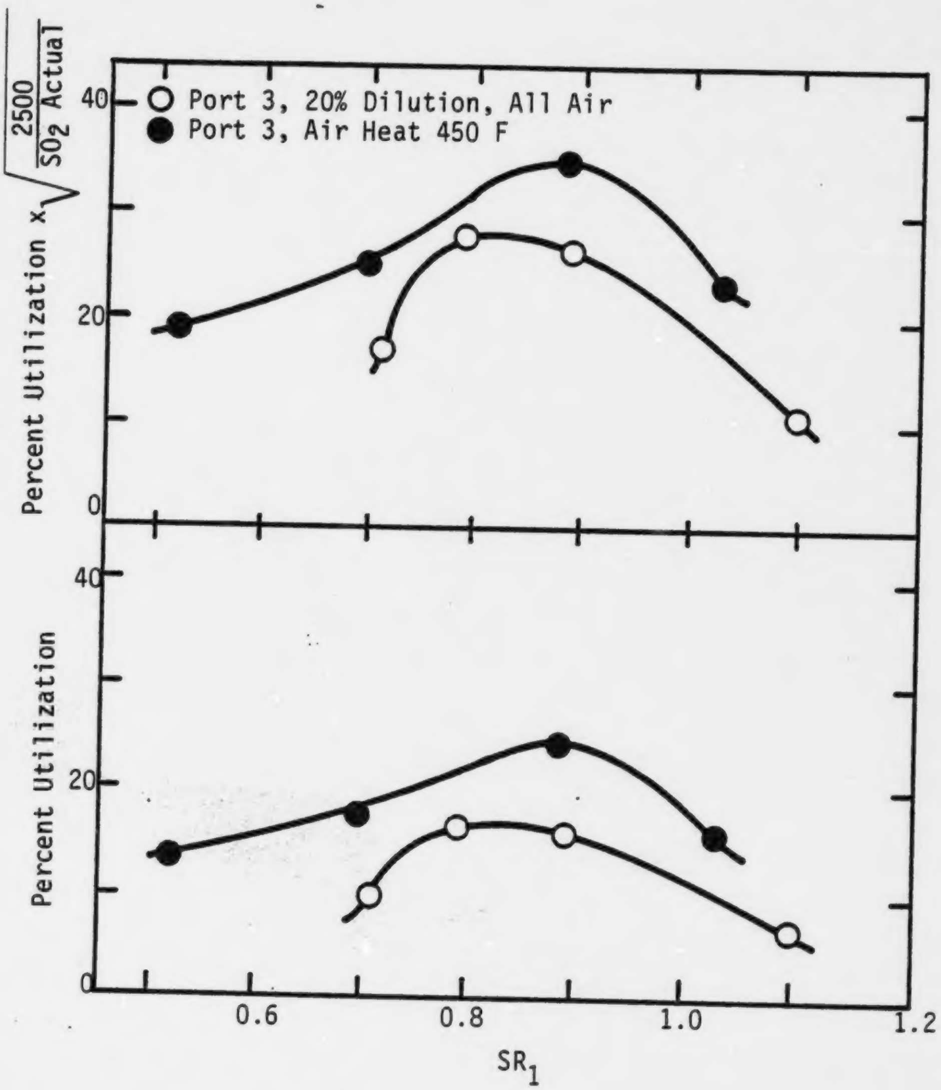


Figure 6-24. Effect of first stage stoichiometry on sulfur capture, two thermal environments, sorbent with staging air. Conditions as in figure 6-19 and 6-21.

7.0 FUEL AND SORBENT EFFECTS BOILER SIMULATOR FURNACE, SERIES C

The first two experimental series, Series A: combustion parameter screening and Series B: sulfur chemistry and thermal environment studies, investigated the effect of various operational and design parameters on the effectiveness of dry sorbent injection for SO_2 control. The third experimental series, Series C: fuel and sorbent effects, was designed to investigate the effect of fuel and sorbent type on sulfur capture by dry sorbents. The phased screening approach used for the bench scale experiments allowed the selection of test conditions for the fuel and sorbent studies from a wide range of characterized conditions. A rigorous test of the effect of fuel and sorbent characteristics on sulfur capture was desired, therefore, combustion conditions were selected to provide a wide range of thermal and chemical environments. Four basic combustion conditions were chosen. These conditions were:

- Burner staged, uncooled, sorbent with the fuel;
- Burner staged, cooled, sorbent with the fuel;
- Burner staged, cooled, sorbent with the tertiary (staging) air;
- Physically staged, uncooled, sorbent with the staging air.

The experiments were all performed in the down-fired BSF at full load (1.0 M Btu/hr). Cooling was in the radiant section only, no air preheat or nitrogen dilution was used. The physically staged experiments were performed at a first stage stoichiometry of 0.9 and an overall stoichiometry of 1.2. The burner-staged studies were at a burner zone stoichiometry of 0.6 and an overall stoichiometry of 1.2.

7.1 Results, Effect of Sorbent Type (Series C-1)

A number of sorbent characteristics which affect sulfur capture have been identified in previous investigations, these characteristics include:

- Form of the alkali salt; i.e., carbonate ($CaCO_3$), oxide (CaO), or hydrate ($Ca(OH)_2$).
- Origin and petrographic characteristics of the stone; i.e., calcite, marl, spar, etc., and such characteristics as grain size.
- Particle size.
- Composition, including impurities such as iron, sodium, chlorine, and potassium.
- Physical characteristics, including pore size distribution and volume, and total surface area.
- Calcination behavior, including decomposition and deadburning characteristics.

It is not possible to vary these parameters independently, it was also outside the scope of this project to attempt to investigate all of these parameters. The five sorbents used varied in:

- Particle Size--two calcites from the same mine and manufacturer had been pulverized and screened to different size fractions.
- Petrographic Character--a calcite and a marl; the calcite typically had a very large (∿550 μm) uniform grain size while the marl was a very fine-grained powdery material which did not require pulverization prior to use.
- Composition--a dolomite ($CaCO_3 \cdot MgCO_3$) and a hydrated lime ($Ca(OH)_2$) in addition to the limestones.

Sorbent Characteristics

Table 7-1 shows the sorbents used and some of the physical and chemical properties of these sorbents. Two sizes of the same calcite limestone, Vicron 45-3 and Vicron 15-15 were used. The calcite was quarried from a midwestern mine, pulverized, classified, and supplied dry in bags. The other limestone used was a marl, dredged from a midwestern marsh, shipped wet, as dug, in drums. The marl when received was partially dried and agglomerated into large hard chunks, it contained lumps of organic matter and grains of sand. The marl was processed for use (so that it could be fed and transported with air) by mixing it with water to form a thin, smooth

TABLE 7-1. SORBENT PROPERTIES

Sorbent	Theo. Comp.	Physical Properties				Chemical Analysis (% Weight [Hazen])							
		Mean Size (μm)	Density (gm/cm^3)	Surface Area (m^2/gm)	Ignition Loss (% Wt. at 2000 F)	Ca	Fe	Al	Na	Mg	K	Si	Cr
Vicron 45-3	$CaCO_3$	11.0	2.757	0.9	44.0	39.2	0.037	0.07	0.022	0.485	0.011	0.07	0.006
Vicron 15-15	$CaCO_3$	3.0	2.740	2.73	44.0	39.3	0.071	0.07	0.017	0.422	0.010	0.08	0.009
Michigan Marl	$CaCO_3$	18.0	2.533	---	42.0	25.0	0.873	1.09	0.188	0.931	0.444	9.29	0.21
Michigan Marl <200 Mesh	$CaCO_3$	11.0	2.533	2.27	36.1	30.1	0.262	0.67	0.119	1.02	0.238	3.63	0.005
Dolomite	$CaCO_3 \cdot MgCO_3$	34.0	2.855	0.64	47.1	21.0	0.102	0.09	0.033	12.1	0.039	0.37	0.27
Hydrated Lime	$Ca(OH)_2$	12.5	2.353	10.4	26.4	48.9	0.164	0.28	0.034	0.255	0.129	1.08	0.005

paste and spreading this paste in the sun to dry. The dried powder was scraped up and sifted through a course screen. The characteristics of this processed stone are shown in Table 7-1. The Michigan marl processed in this manner still contained significant impurities, as reflected by the high Al, Fe, and Si content. The stone also gave very poor capture in early coal and propane fired tests. Therefore, the sorbent was further sieved to pass a 200 mesh (74 μm) screen. The characteristics of this creened stone are also shown in Table 7-1. Two other sorbents, dolomitic limestone, obtained from the same midwestern mine which supplied dolomite for the TVA pilot scale tests, and a hydrated, or slaked, lime (which was also used for the 2667 pilot scale studies) were used.

The composition, surface area and other characteristics of these stones are shown in Table 7-1. The overall particle size distribution of the sorbents used was determined by sedimentation. Figures 7-2 through 7-7 show particle size distributions for the six stones (including the two Michigan marls). The mean size shown in Table 7-1 is the mass mean size, taken from the data in Figures 7-2 through 7-7.

The ability to assess sorbent reactivity is of key importance. Two standard methods of characterizing sorbent reactivity were employed. One method of assessing the degree of deadburning of a calcine is to determine the rate of disassociation of the calcine in water. A calcine which has been deadburned will dissociate more slowly than one with the open porous structure typical of a "softburned" stone. A deadburned stone will be less reactive than a stone which is softburned because when a particle deadburns, the pore structure begins to collapse and less surface area is available for reaction with sulfur. The rate of dissociation of a sorbent in water is conveniently measured by stirring a known amount of stone in water and titrating the solution with acid to a constant pH (generally to the neutral point, 7.0) at timed intervals. The time it takes a stone to dissociate completely (or to add the acid equivalent to the stone) is a simple measure of the sorbent's reactivity. This dissociation test is only useful for unsulfated stones and cannot be used on sorbent/fly ash mixtures because the presence of acidic or basic compounds will interfere with titration of the sorbent to the neutral point.

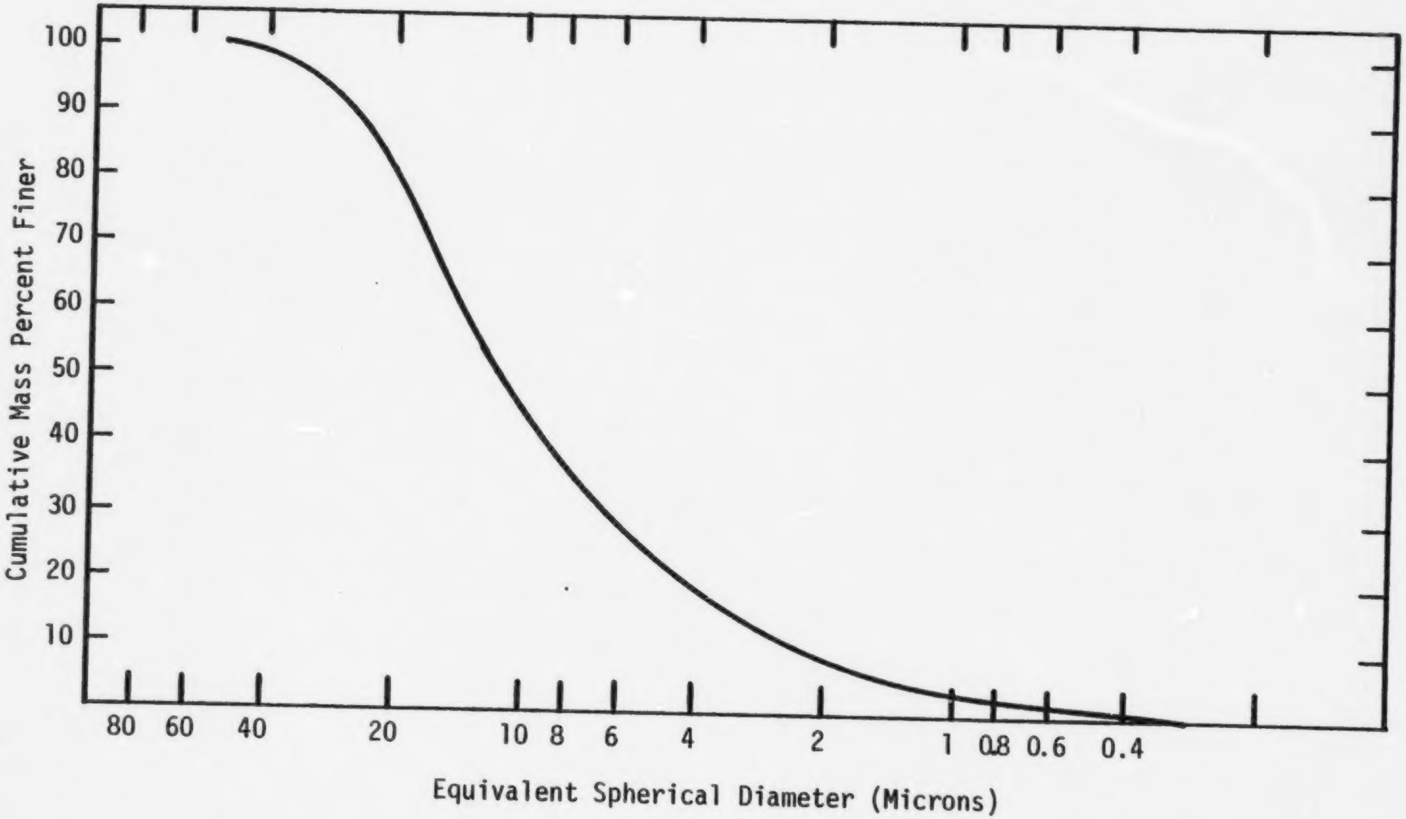


Figure 7-2. Particle size distribution, Vicron 45-3 ($CaCO_3$).

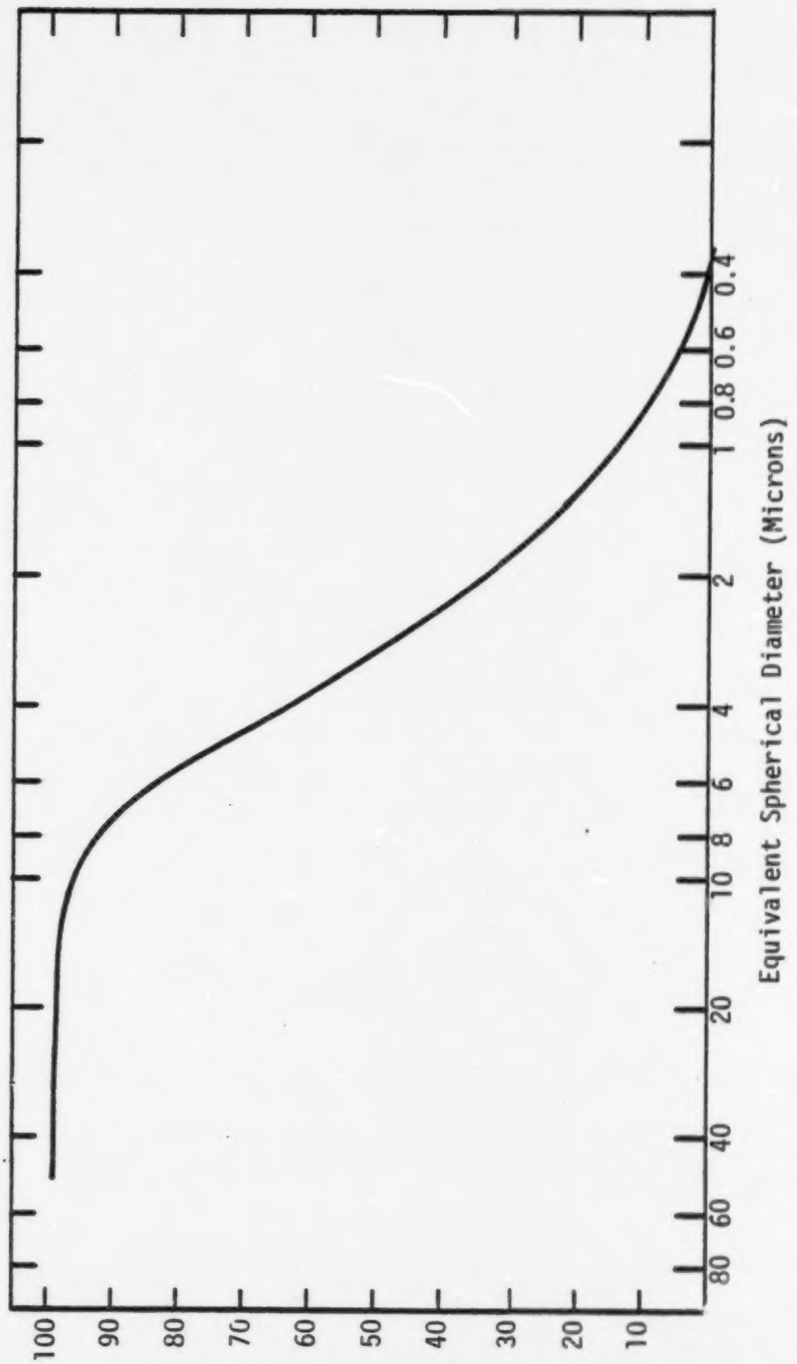


Figure 7-3. Particle size distribution, Vicron 15-15 ($CaCO_3$).

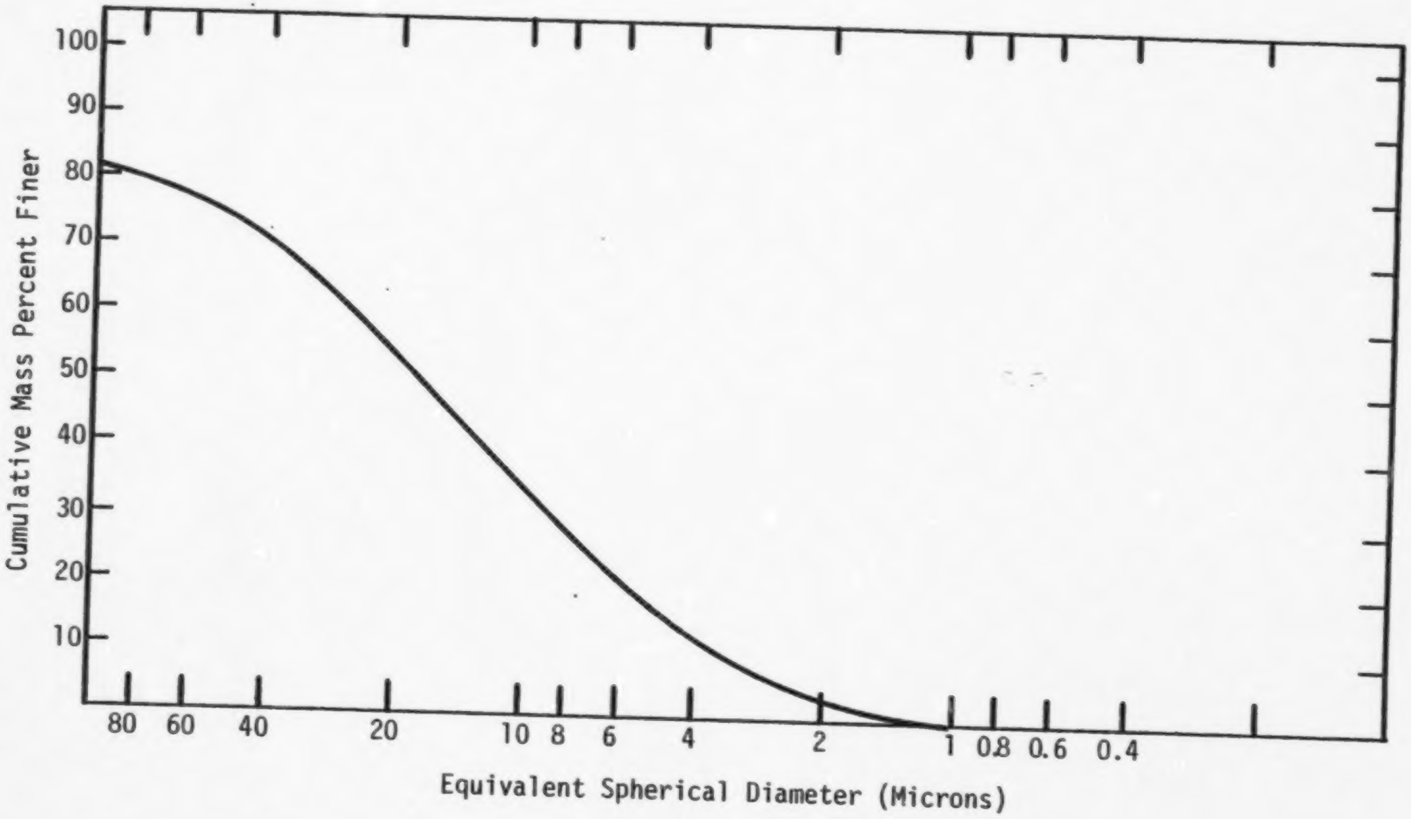


Figure 7-4. Particle size distribution, Michigan marl ($CaCO_3$).

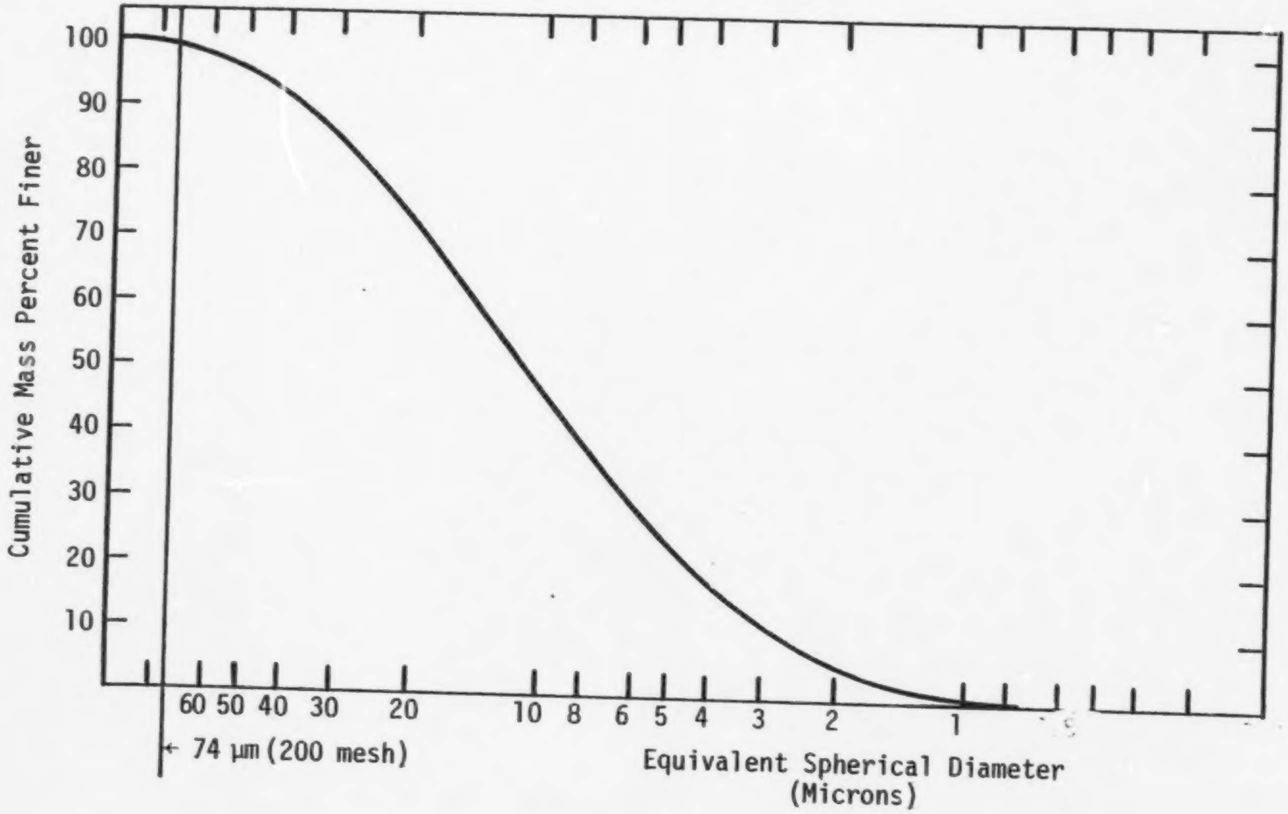


Figure 7-5. Particle size distribution, Michigan marl (<200 mesh).

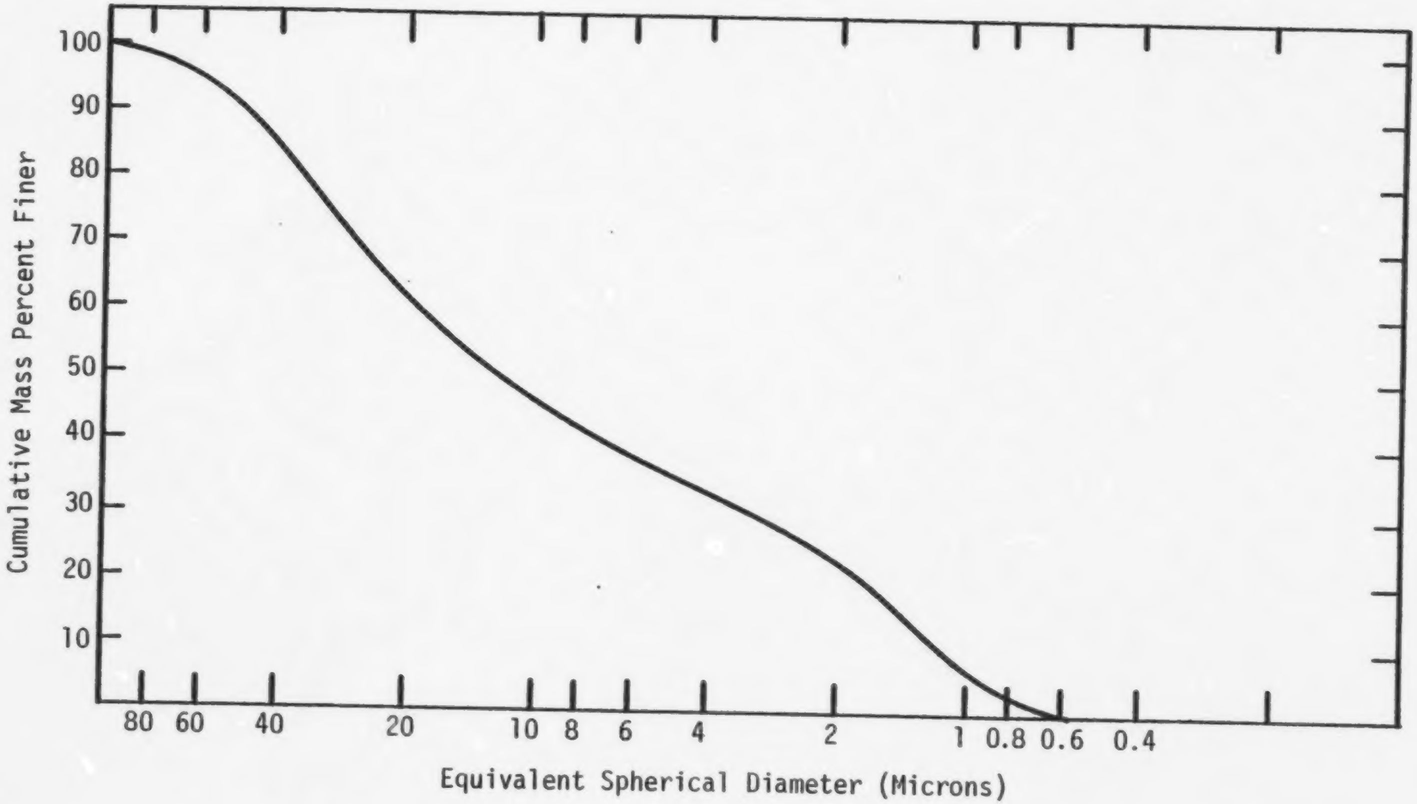


Figure 7-6. Particle size distribution, hydrated lime ($Ca(OH)_2$).

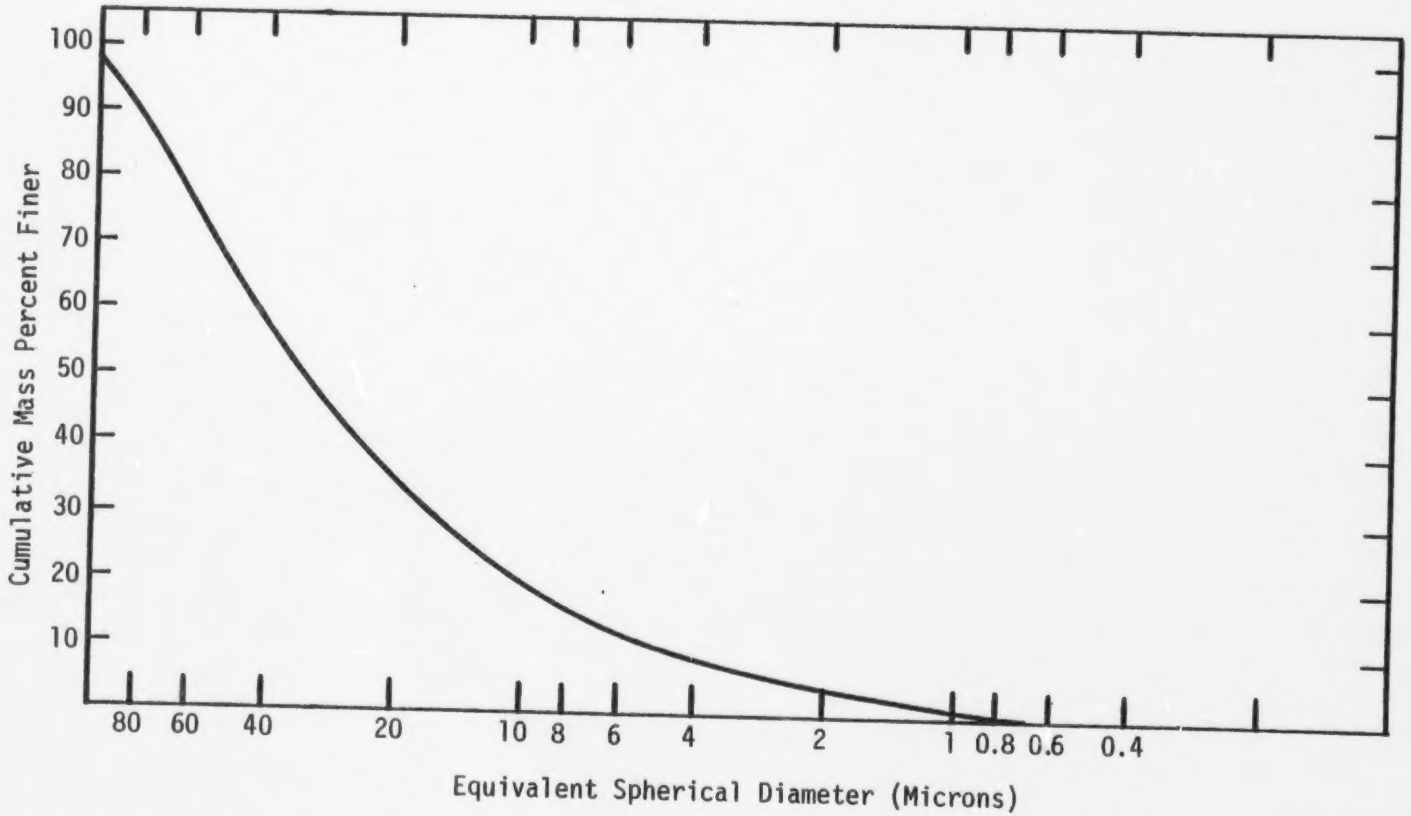


Figure 7-7. Particle size distribution, dolomite ($CaCO_3 \cdot MgCO_3$).

The dissociation characteristics of various calcines are different; however, the dissociation rate of a given stone is affected by deadburning in a predictable manner. The dissociation characteristics of the five sorbents calcined at various temperatures was determined. Figures 7-8 through 7-12 show the measured characteristics of the sorbents calcined for two hours at various temperatures between 1700°F and 2600°F. It is clear that the conditions which result in deadburning (corresponding to slow dissociation in water) are different for different stones. The results for the hydrated lime and for the dolomite represent two extremes in calcination behavior. The dolomite does not appear to be deadburned even at the highest temperature (2600°F), while the hydrated lime was deadburned at 2000°F.

A second test for the degree of overburn or deadburning of a sorbent is the hydration weight gain of the solid. The solid sample is dried at a temperature sufficient to remove moisture associated with the particles water is added, allowed to react with the solids, and evaporated. The weight gain associated with this water uptake can be related to the degree of overburn of the sorbent. The hydration weight gain test may be used on sulfated samples and on sorbent/ash mixtures. However, the interpretation of the weight gain results requires the characterization of the pure sorbent in terms of deadburning versus dissociation rate and deadburning versus hydration weight gain. A characteristic weight gain for a deadburned or softburned sorbent is established and compared to weight gains measured for some of the standard calcines described earlier. Table 7-2 shows hydration weight gains of some of the standard calcines.

Effect of Sorbent on Sulfur Capture, Results

The effect of sorbent type on sulfur capture at four firing conditions was investigated. The test matrix for the fuel/sorbent studies is shown in Table 7-3. Sulfur capture for each sorbent at each condition was measured through the furnace, at sample ports 1, 2, and 3. Calcium-to-sulfur ratios were based on sorbent feed-rate and calcium content and fuel-sulfur content. The first condition used was the Indiana 3 coal fired with the subscale distributed-mixing burner (burner staged) at a burner zone stoichiometry

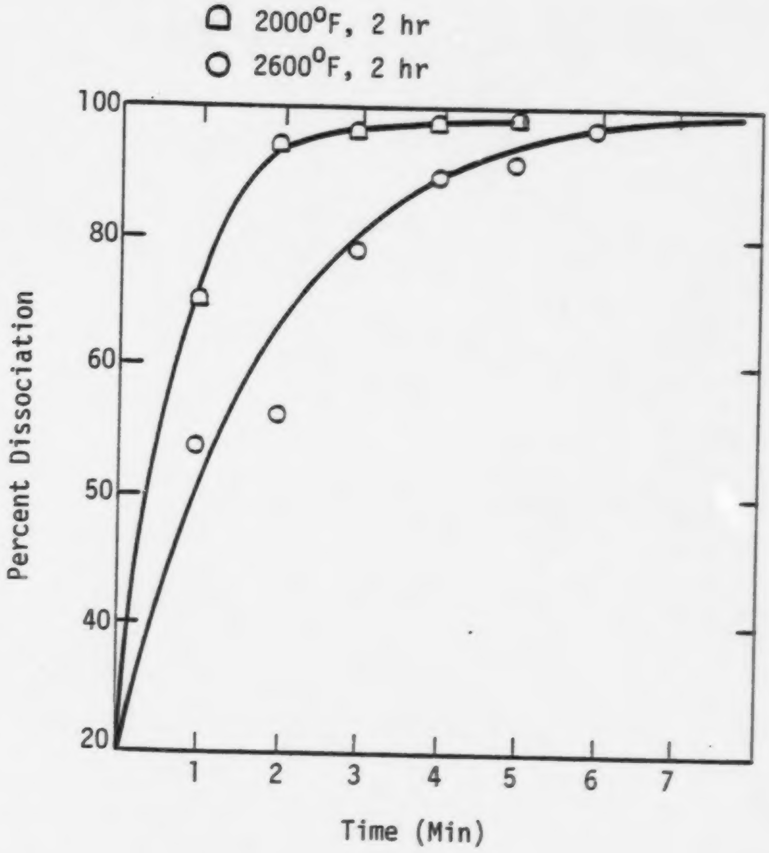


Figure 7-8. Reactivity test - standard calcine of Vicron 45-3.

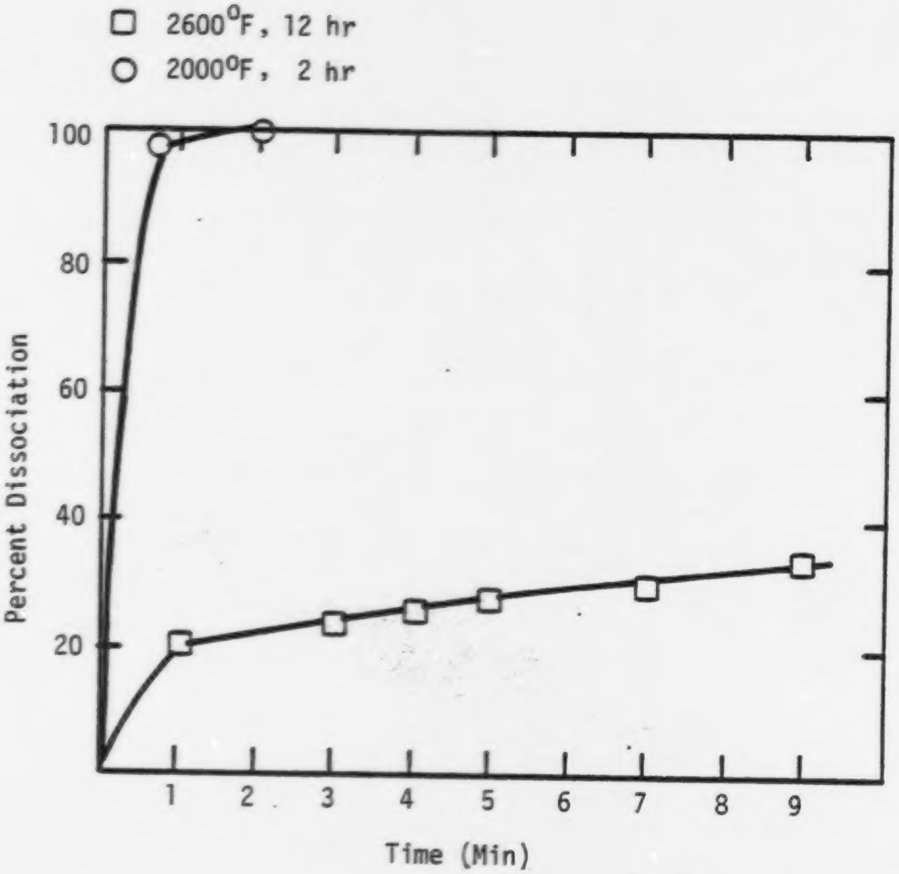


Figure 7-9. Reactivity test - standard calcine of Vicron 15-15.

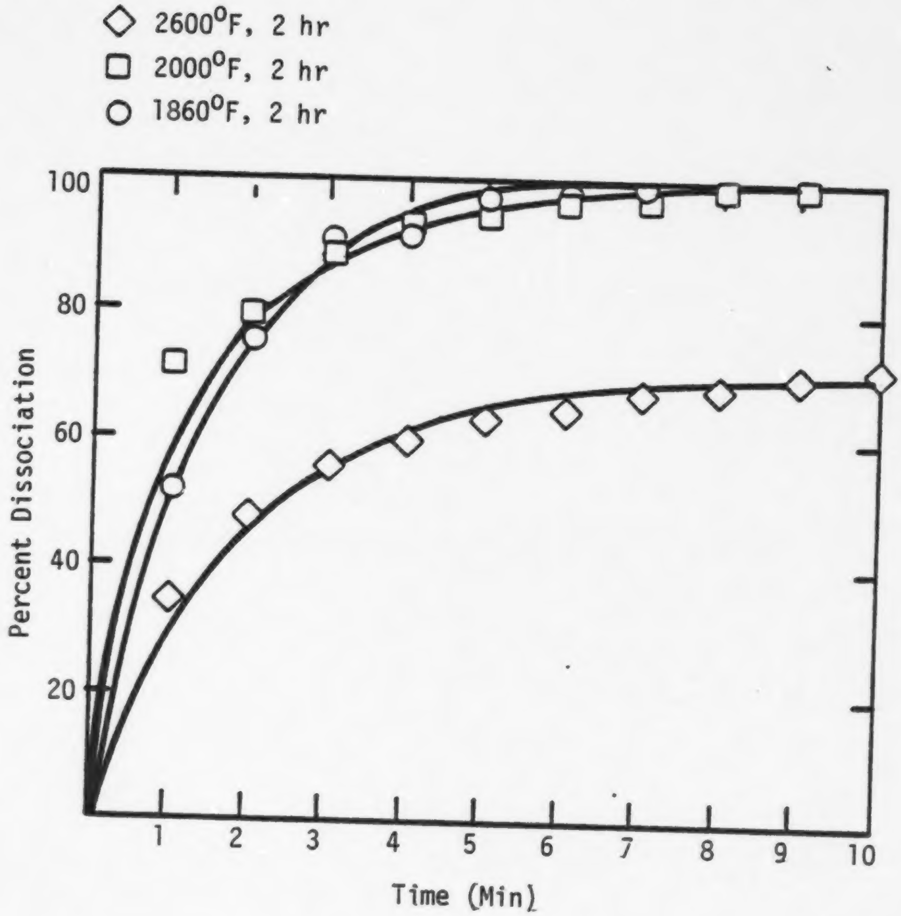


Figure 7-10. Reactivity test - standard calcine of Michigan marl.

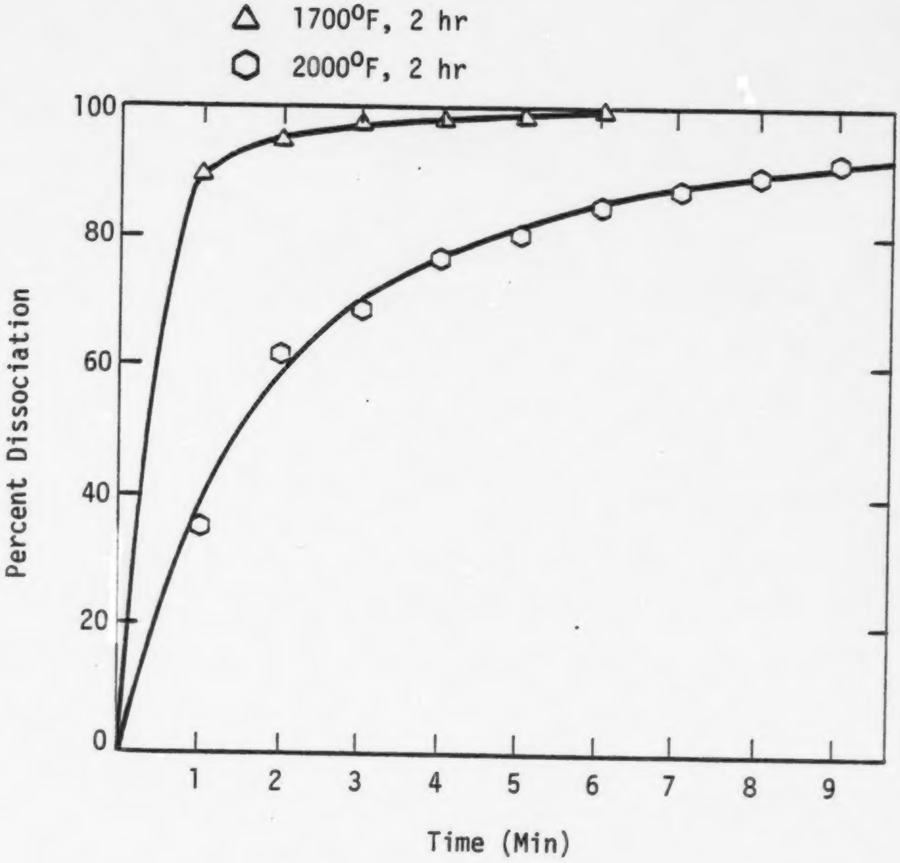


Figure 7-11. Reactivity test - standard calcine of hydrated Colton lime ($Ca(OH)_2$).

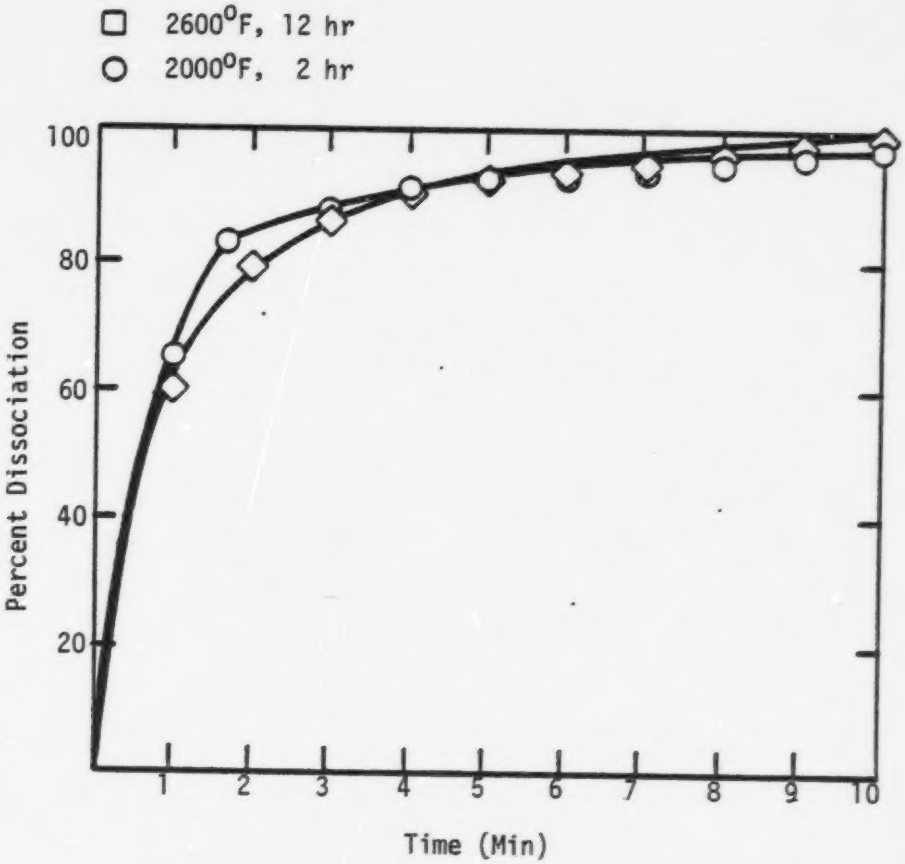


Figure 7-12. Reactivity test, standard calcine of dolomite ($CaCO_3 \cdot MgCO_3$).

TABLE 7-2. HYDRATION WEIGHT GAIN OF SELECTED SORBENT CALCINES

Sorbent	Temp. (°F)	Wt. Gain (%)	Temp. (°F)	Wt. Gain (%)
Vicron 45-3	2000	33.08	2650	33.24
Vicron 15-15	2000	34.26	2780	14.99
Mich. Marl	2000	31.56	2650	19.57
Dolomite	2000	67.50	2780	42.06
$Ca(OH)_2$	1700	32.85	2000	33.25

TABLE 7-3. FUEL AND SORBENT EFFECTS TEST MATRIX (SERIES C)

Combustion Conditions	Fuel	Sorbent														
		Vicron 45-3 $CaCO_3$			Vicron 15-15 $CaCO_3$			Dolomite $CaCO_3 \cdot MgCO_3$			Marl $CaCO_3$			$Ca(OH)_2$		
		Ca/S			Ca/S			Ca/S			Ca/S			Ca/S		
		0	1.5	2.5	0	1.5	2.5	0	1.5	2.5	0	1.5	2.5	0	1.5	2.5
DMB, 0.6, 1.2 Uncooled Sorbent with Fuel	I3	X	X	X	X	X	X	X	X	X	X	X[a]	X[a]	X	X	X
	P	X	X	X	X	X	X	X	X	X	X	X[a]	X[a]	X	X	X
	CWS	X	X	X												
	B	X	X	X												
DMB, 0.6, 1.2 Cooled Sorbent with Fuel	I3	X	X	X	X	X	X	X	X	X	X	X[b]	X[b]	X	X	X
	P															
	CWS															
	B															
DMB, 0.6, 1.2 Cooled Sorbent With Tertiary Air	I3	X	X	X	X	X	X	X	X	X	X	X[b]	X[b]	X	X	X
	P															
	CWS															
	B															
Externally Staged $SR_1 = 0.9$ Sorbent with Staging Air	I3	X	X	X	X	X	X	X	X	X	X	X	X[b]	X[b]	X	X
	P															
	CWS															
	B															

I3 = Indiana 3 B = Beulah CWS = Coal/Water Slurry P = Propane

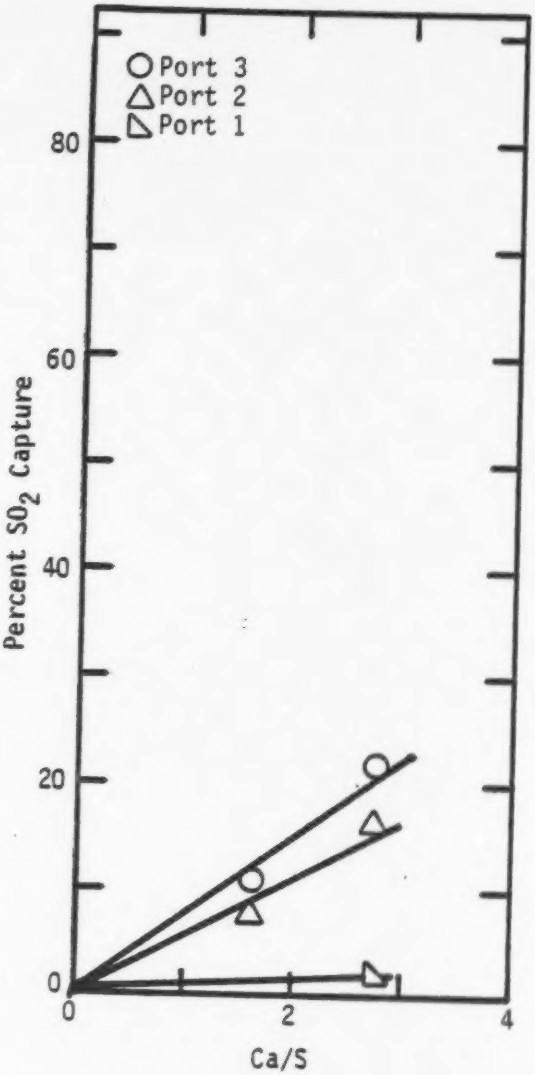
a - with all size fraction and <200 mesh fraction
b - with <200 mesh fraction only

of 0.6 and an overall stoichiometry of 1.2. The sorbent was added with the fuel. Figures 7-13 through 7-18 summarize sulfur capture at each port for these conditions using six sorbents: two size fractions of Vicron, 45-3 and 15-15, the Michigan marl "as-received" and sifted to below 200 mesh (which changed the composition as well as the size distribution as summarized in Table 7-1), hydrated lime, and dolomite. Sulfur capture by all of the sorbents, except dolomite, was poor. The removal of the large particles (and concommitant impurities) from the Michigan marl improved the sulfur capture but not dramatically. The smaller sized Vicron (15-15, 3 μm mean size) gave very slightly better sulfur capture under these conditions than the Vicron 45-3 (11 μm mean size). The dolomite gave surprisingly good capture, about 18 percent utilization of the calcium as opposed to 11 percent or less for the other sorbents. It is interesting to note that most of the capture took place in the postflame section; capture in the radiant furnace was minimal.

A set of water-cooled coils was added at the top of the radiant furnace to cool the region immediately adjacent to the burner. Five sorbents (only the < 200 mesh marl was used) were tested. The sorbents were added with the fuel and the firing system was as described: internally staged, $SR_B = 0.6$, $SR_T = 1.2$. The cooling coils removed about 9 percent (or ∿ 90,000 Btu/hr) of the total input heat from the radiant section. The data plotted in Figures 7-19 through 7-23 summarize the sulfur capture measured throughout the furnace for the five sorbents under these conditions.

Cooling improved the sulfur capture of all of the sorbents except the Vicron 15-15 and the Michigan marl. Cooling the radiant furnace increased the proportion of the total sulfur capture occurring in the radiant furnace.

Figures 7-24 through 7-28 show data for the sulfur capture of the five sorbents under the same cooled conditions except that the sorbent was added with the tertiary air (through the outboard staging air ports in the firing face). This change in sorbent location resulted in a small increase in the sulfur capture for all of the stones except the Vicron 15-15. This increase in sulfur capture was again accompanied by an increase in the capture in the radiant section. The insensitivity of the Vicron 15-15 to both sorbent location and cooling in the radiant section is puzzling. It may be that the

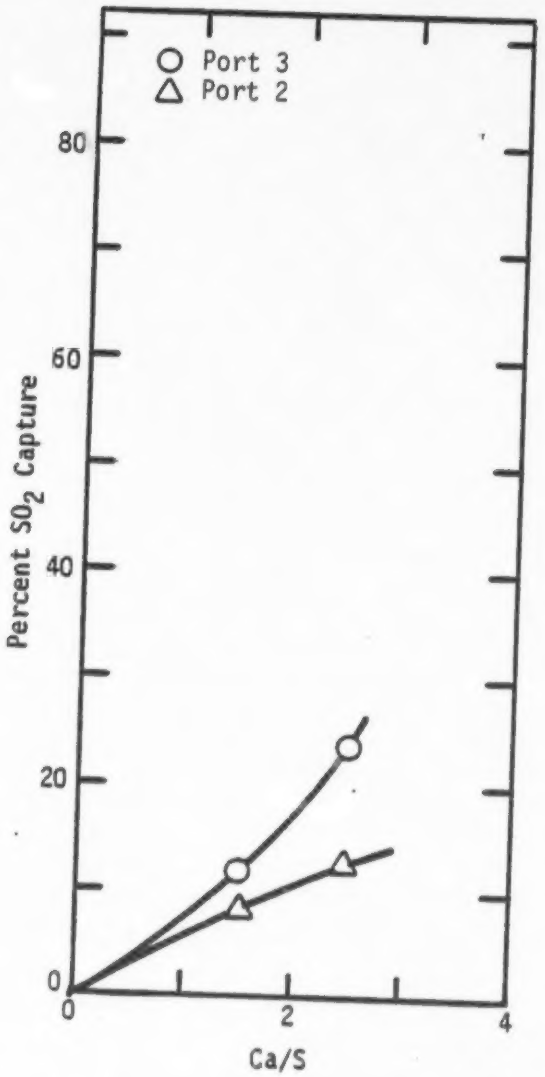


Fuel: Indiana 3
Staging: Internal
Cooling: None
Sorbent Loc.: With Fuel

SO_2:

Load: 1.0 MBtu/hr
Run: 5-25,5-8
Ca/S: Shown
Sorbent: Vicron 45-3
SRp: 0.18
SR_b: 0.59-0.60
SR_T: 1.16-1.19

Figure 7-13. Sulfur capture for Vicron 45-3, uncooled, internally staged.

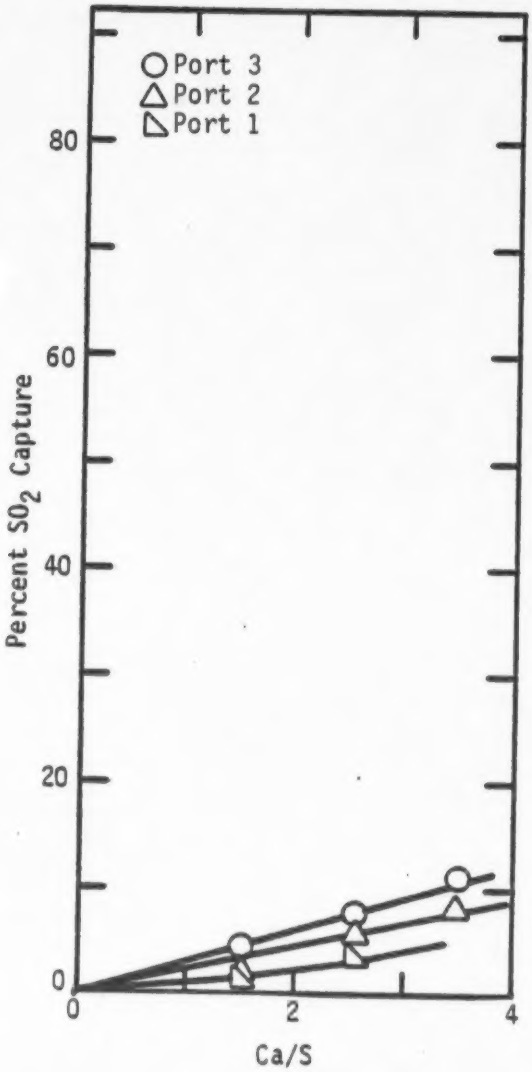


Fuel: Indiana 3
Staging: Internal
Cooling: None
Sorbent Loc.: With Fuel

SO_2:

Load: 1.03-1.04 MBtu/hr
Run: 5-19,5-8
Ca/S: Shown
Sorbent: Vicron 15-15
SRp: 0.18-0.19
SR_b: 0.59-0.60
SR_T: 1.16-1.19

Figure 7-14. Sulfur capture for Vicron 15-15, uncooled, internally staged.

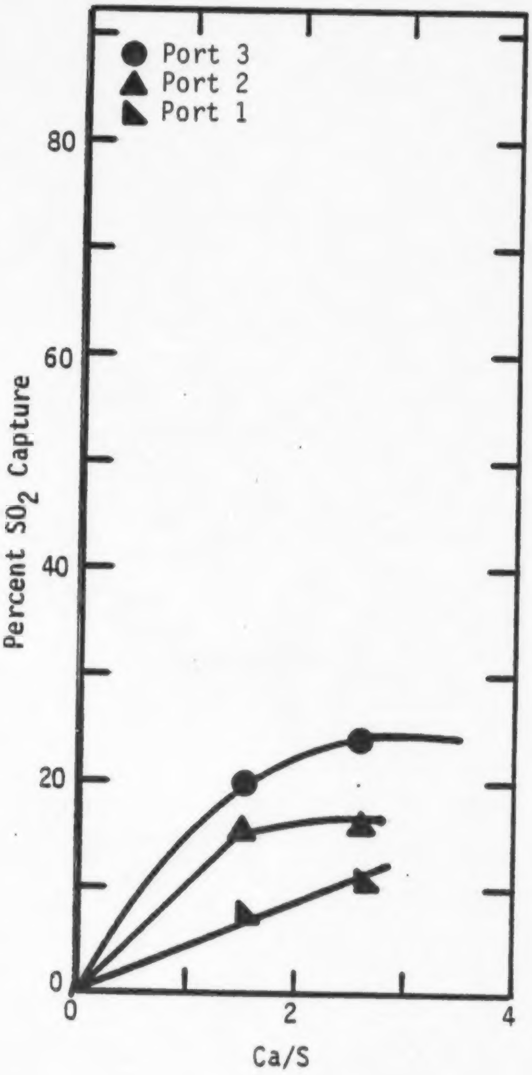


Fuel: Indiana 3
Staging: Internal
Cooling: None
Sorbent Loc.: With Fuel

SO_2:

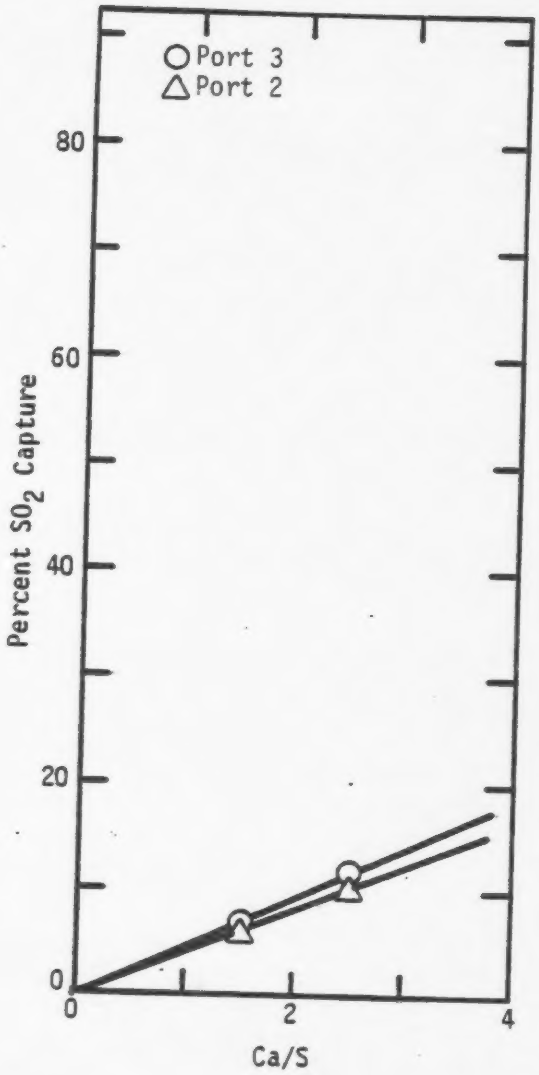
Load: 1.01-1.02 MBtu/hr
Run: 5-24-1,6
Ca/S: Shown
Sorbent : Michigan marl
SRp: 0.19-0.20
SR_b: 0.60-0.61
SR_T: 1.19-1.20

Figure 7-15. Sulfur capture for Michigan marl, uncooled, internally staged.



Fuel: Indiana 3	Load: 1.02-1.03 MBtu/hr
Staging: Internal	Run: 5-28-1,4
Cooling: None	Ca/S: Shown
Sorbent Loc.: With Fuel	Sorbent: Michigan marl, <200 mesh
	SRp: 0.18-0.19
SO_2:	SR_b: 0.57-0.59
	SR_T: 1.14-1.18

Figure 7-16. Sulfur capture for Michigan marl <200 mesh, uncooled, internally staged.

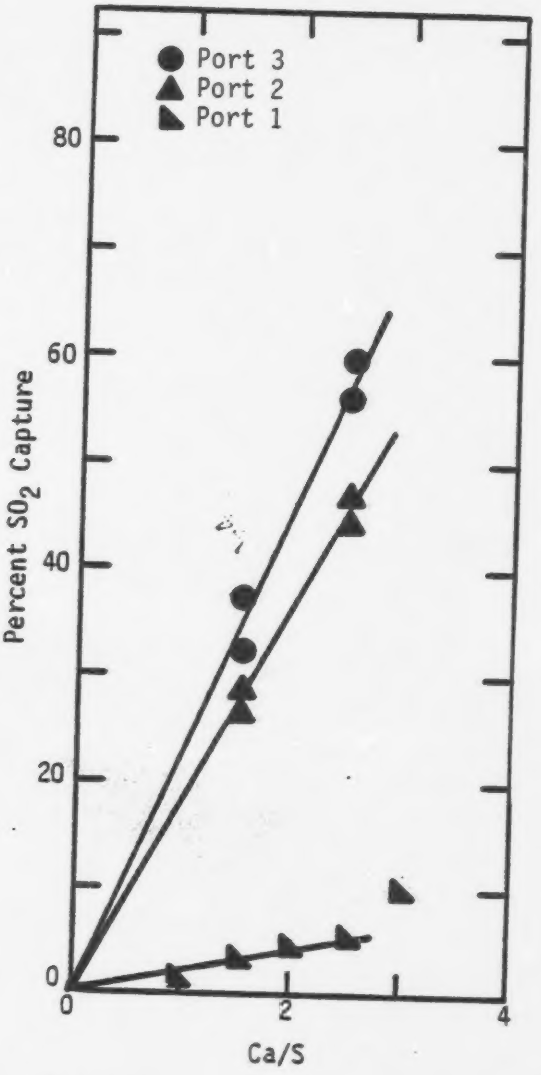


Fuel: Indiana 3
Staging: Internal
Cooling: None
Sorbent Loc.: With Fuel

SO_2:

Load: 1.02 MBtu/hr
Run: 5-20-5,8
Ca/S: Shown
Sorbent: $Ca(OH)_2$
SR_p: 0.19
SR_b: 0.60-0.61
SR_T: 1.17-1.20

Figure 7-17. Sulfur capture for hydrated lime, uncooled, internally staged.

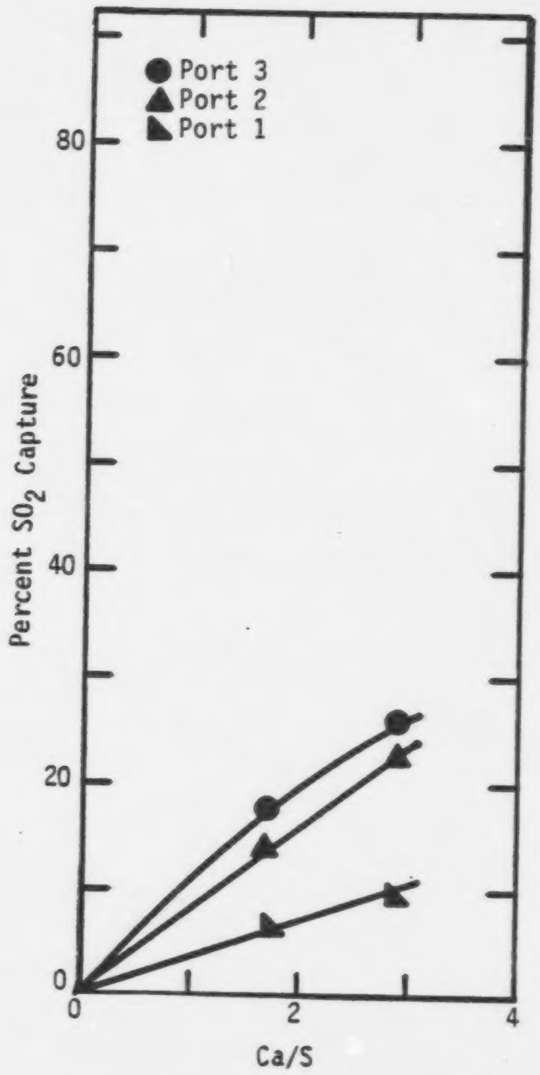


Fuel: Indiana 3
Staging: Internal
Cooling: None
Sorbent Loc.: With Fuel

SO_2:

Load: 1.02-1.06 MBtu/hr
Run: 5-27, 5-18-5,8
Ca/S: Shown
Sorbent: Dolomite
SRp: 0.18-0.19
SR_b: 0.59-0.61
SR_T: 1.15-1.20

Figure 7-18. Sulfur capture for dolomite, uncooled, internally staged.

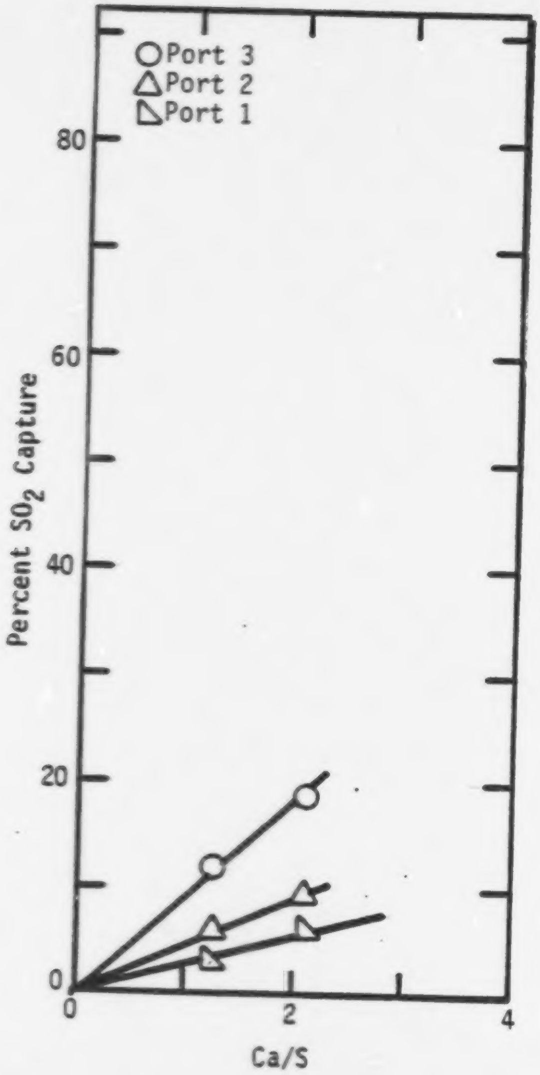


Fuel: Indiana 3
Staging: Internal
Cooling: Radiant
Sorbent Loc.: With Fuel

SO_2:

Load: 1.0-1.08 M Btu/hr
Run: 6-3, 6.9
Ca/S: Shown
Sorbent: Vicron 45-3
SRp: 0.16-0.18
SR_b: 0.59-0.61
SR_T: 1.17-1.20

Figure 7-19. Sulfur capture for Vicron 45-3, cooled, sorbent with fuel.

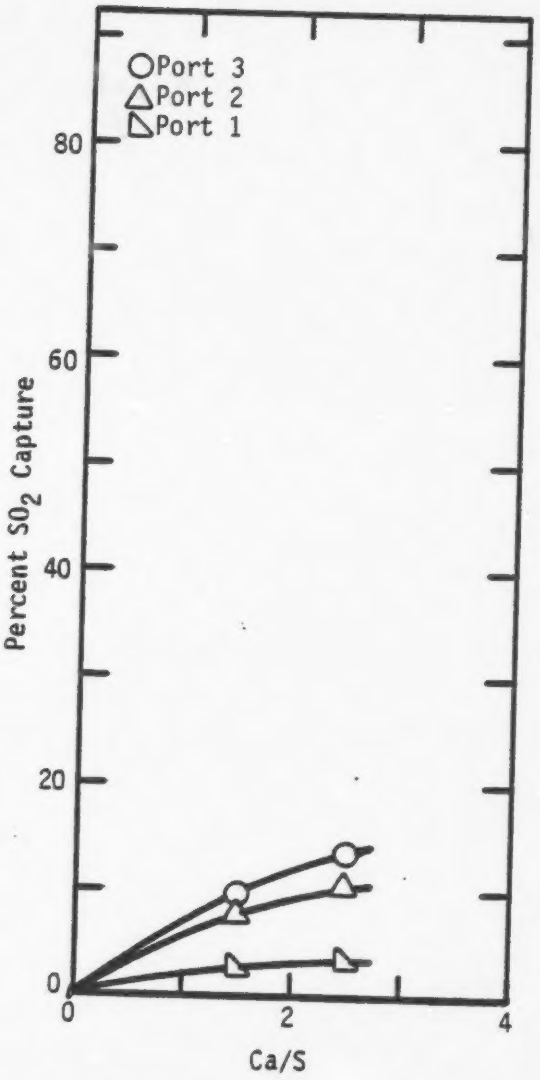


Fuel: Indiana 3
Staging: Internal
Cooling: Radiant
Sorbent Loc.: With Fuel

SO_2:

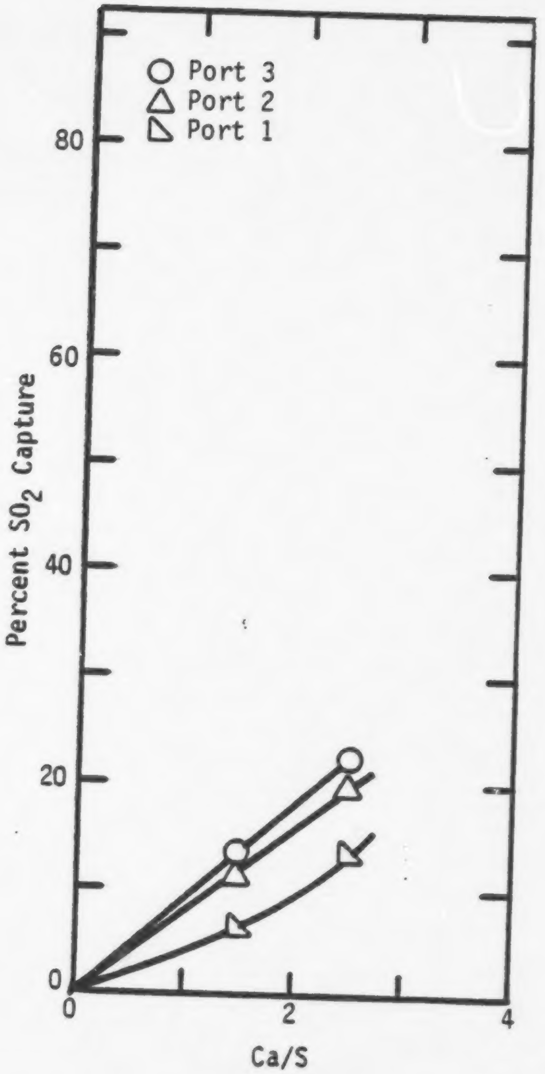
Load: 1.01 M Btu/hr
Run: 6-11
Ca/S: Shown
Sorbent: Vicron 15-15
SRp: 0.18-0.19
SR_B: 0.59-0.60
SR_T: 1.18-1.20

Figure 7-20. Sulfur capture for Vicron 15-15, cooled, sorbent with fuel.



Fuel: Indiana 3	Load: 1.02-1.03 M Btu/hr
Staging: Internal	Run: 6-10
Cooling: Radiant	Ca/S: Shown
Sorbent Loc.: With Fuel	Sorbent: Michigan Marl <200 mesh
SO_2:	SRp: 0.18-0.19
	SR_b: 0.61-0.62
	SR_T: 1.18-1.21

Figure 7-21. Sulfur capture for Michigan marl, <200 mesh, cooled, sorbent with fuel.

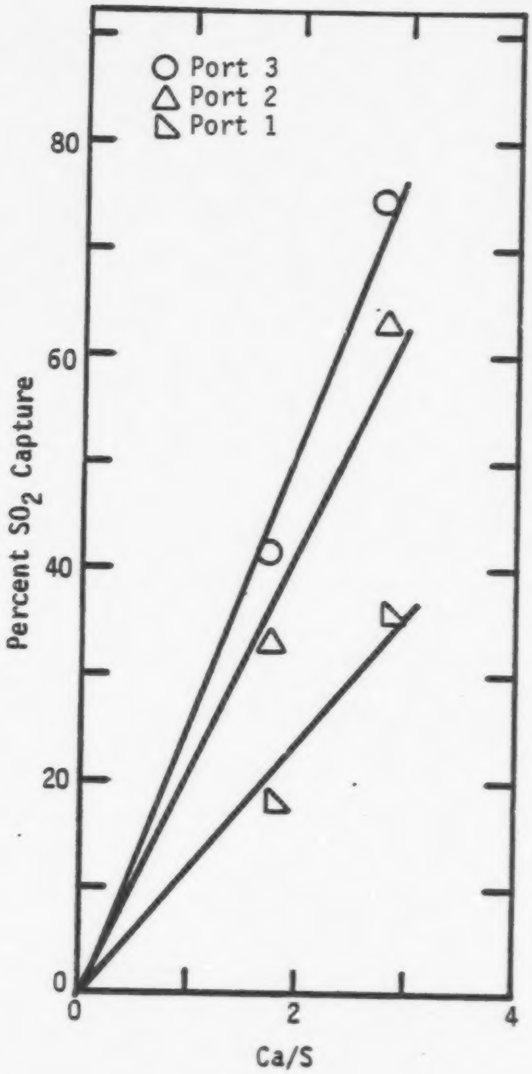


Fuel: Indiana 3
Staging: Internal
Cooling: Radiant
Sorbent Loc.: With Fuel

SO_2:

Load: 1.03 M Btu/hr
Run: 6-9
Ca/S: Shown
Sorbent: $Ca(OH)_2$
SRp: 0.17-0.18
SR_b: 0.60
SR_T: 1.19-1.20

Figure 7-22. Sulfur capture for hydrated lime, cooled, sorbent with fuel.

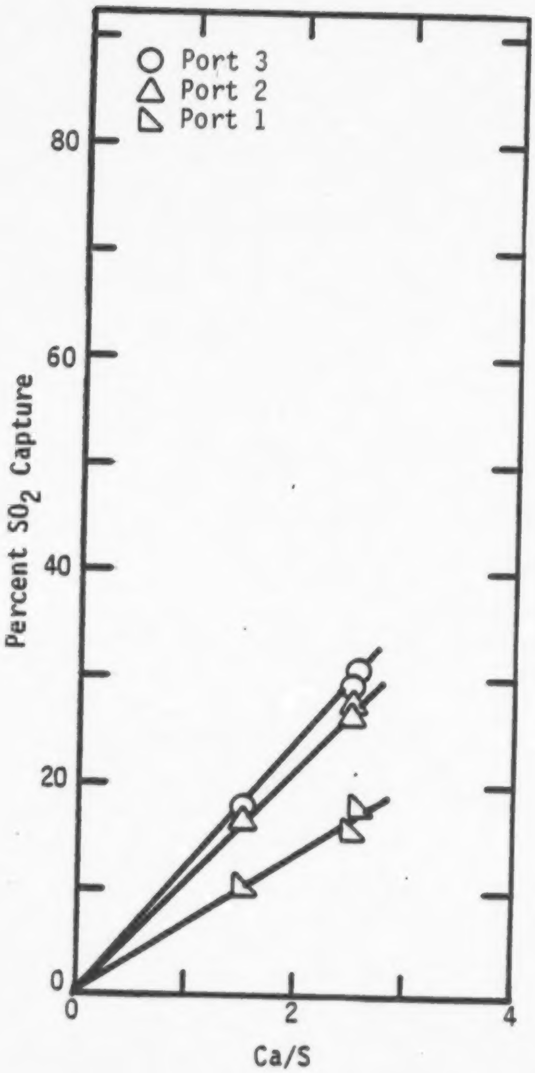


Fuel: Indiana 3
Staging: Internal
Cooling: Radiant
Sorbent Loc.: With Fuel

SO_2:

Load: 1.0-1.01 M Btu/hr
Run: 6-8
Ca/S: Shown
Sorbent: Dolomite
SRp: 0.12
SR_b: 0.59-0.60
SR_T: 1.18-1.21

Figure 7-23. Sulfur capture for dolomite, cooled, sorbent with fuel.

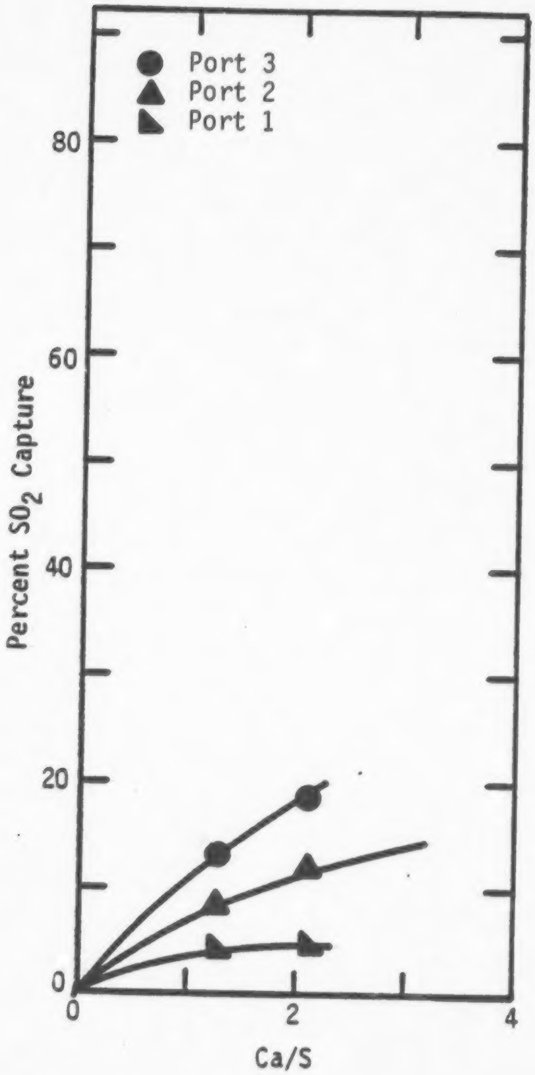


Fuel: Indiana 3
Staging: Internal
Cooling: Radiant
Sorbent Loc.: With T.A.

SO_2:

Load: 1.0-1.01 M Btu/hr
Run: 6-4
Ca/S: Shown
Sorbent: Vicron 15-15
SR_p: 0.12
SR_b: 0.56-0.59
SR_T: 1.14-1.19

Figure 7-24. Sulfur capture for Vicron 15-15, cooled, sorbent with tertiary air.

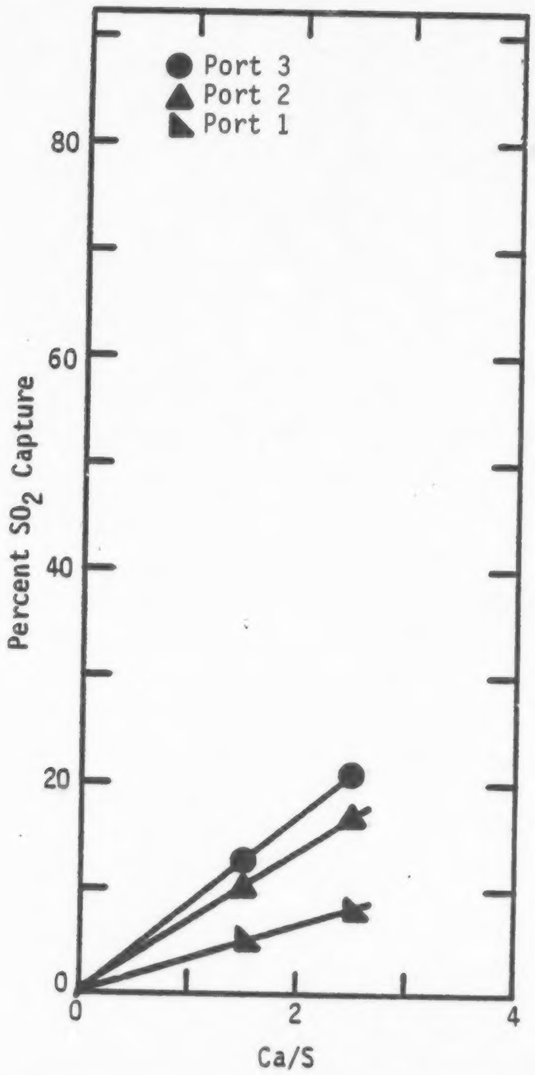


Fuel: Indiana 3
Staging: Internal
Cooling: Radiant
Sorbent Loc.: With T.A.

SO_2:

Load: 1.01 M Btu/hr
Run: 6-11
Ca/S: Shown
Sorbent: Vicron 15-15
SRp: 0.12
SR_b: 0.58-0.59
SR_T: 1.17-1.18

Figure 7-25. Sulfur capture for Vicron 15-15, cooled, sorbent with the tertiary air.

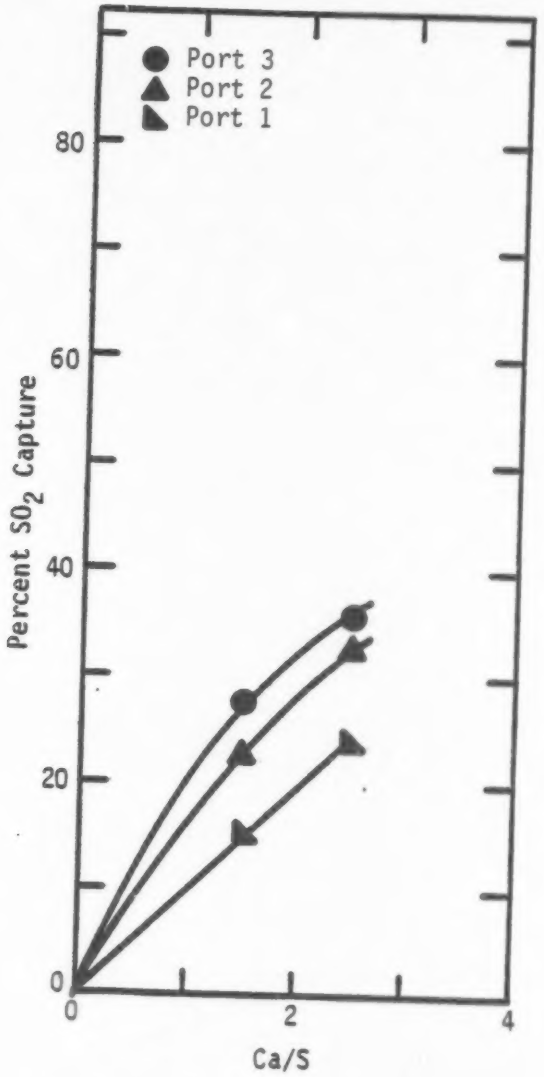


Fuel: Indiana 3
Staging: Internal
Cooling: Radiant
Sorbent Loc.: With T.A.

SO_2:

Load: 1.0 M Btu/hr
Run: 6-10
Ca/S: Shown
Sorbent: Michigan marl <200 mesh
SR_p: 0.12
SR_b: 0.60
SR_T: 1.18-1.19

Figure 7-26. Sulfur capture for Michigan marl <200 mesh, sorbent with the tertiary air.

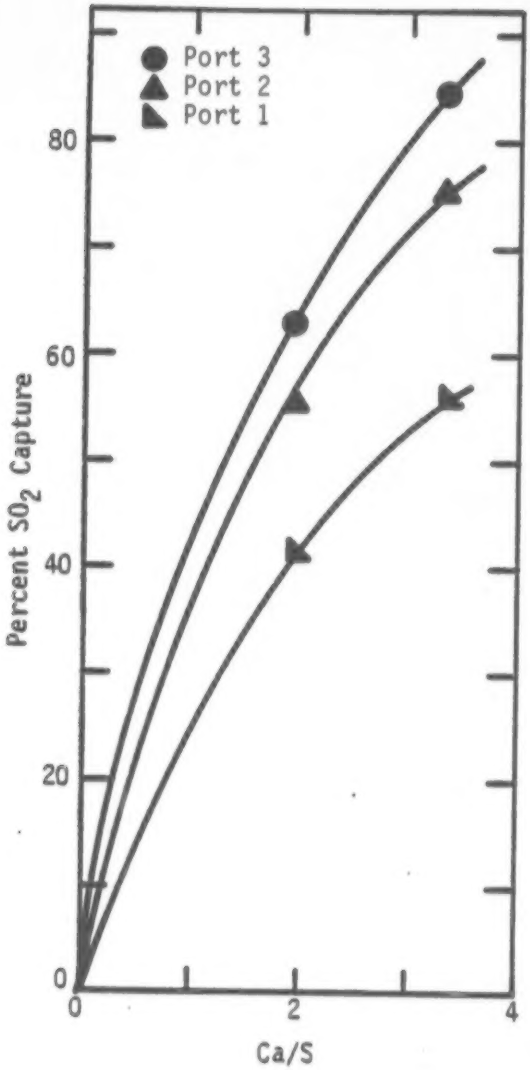


Fuel: Indiana 3
Staging: Internal
Cooling: Radiant
Sorbent Loc.: With T.A.

SO_2:

Load: 1.01-1.02 M Btu/hr
Run: 6-9
Ca/S: Shown
Sorbent: $Ca(OH)_2$
SR_p: 0.15
SR_b: 0.59-0.60
SR_T: 1.16-1.18

Figure 7-27. Sulfur capture for hydrated lime, cooled, sorbent with the tertiary air.



Fuel: Indiana 3
Staging: Internal
Cooling: Radiant
Sorbent Loc.: With T.A.

SO_2:

Load: 1.01-1.02 M Btu/hr
Run: 6-8
Ca/S: Shown
Sorbent: Dolomite
SR_p: 0.17-0.18
SR_b: 0.54-0.60
SR_T: 1.17-1.18

Figure 7-28. Sulfur capture for dolomite, cooled, sorbent with the tertiary air.

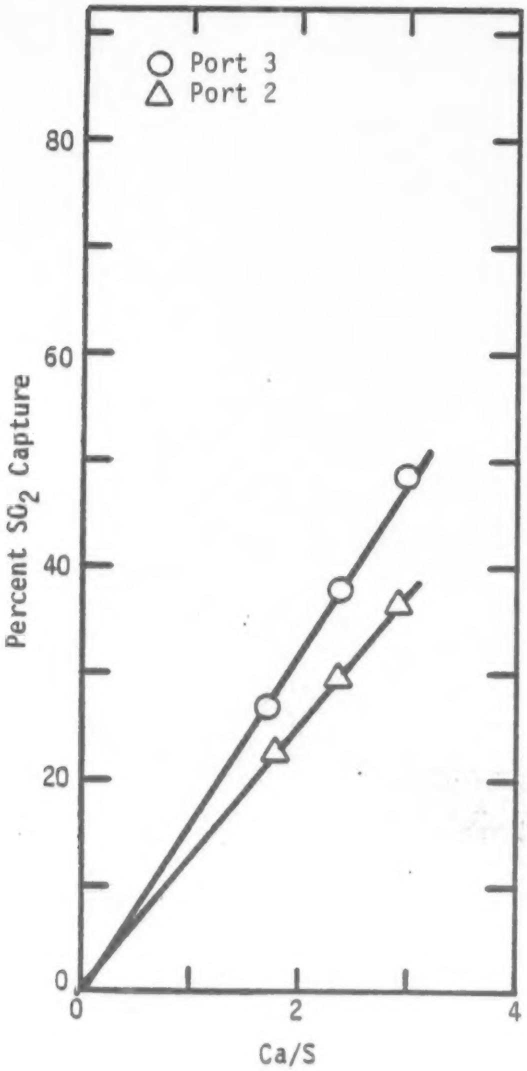
very fine limestone particles agglomerate and are fed into the furnace in sticky lumps which do not break up. These lumps may not calcine well and/or may increase mass-transfer problems.

The next set of figures show sulfur capture for the five sorbents (again only the < 200 mesh marl was used) under externally (physically) staged conditions. The flame was staged by adding fuel and a substoichiometric amount of air at the burner, running the entire radiant zone fuel rich and adding the remainder of the combustion air at the base of the postflame section. The furnace was fired with Indiana 3 coal at a first stage stoichiometry of 0.9. There was no additional cooling in the furnace and the sorbent was added with the staging air. The data plotted in Figures 7-29 through 7-33 show the sulfur capture obtained for the five sorbents under externally staged conditions. The sorbent utilization for all of the stones was higher than for the uncooled, burner staged conditions. There is little data for capture at Port 1 since this sample location is immediately after (∿ 18" downstream) of the staging air addition. Capture through the convective sections was low.

Effect of Sorbent on Sulfur Capture, Discussion

The effect of sorbent type on sulfur capture at the four firing conditions is summarized in Figures 7-34 through 7-37. Overall sulfur capture (measured at Port 3) as a function of calcium-to-sulfur ratio is shown; the thermal histories shown are calculated from measured wall temperatures and mass flow rates assuming plug flow. The shaded area (in the temperature versus residence time plots) indicates the variation in thermal environment for each set of experiments. Wall temperatures in the radiant section are lower than gas temperatures, especially for the cooled conditions where the temperature difference may be as much as 800^{o}F right at the cooling coils. The low initial temperatures shown in Figures 7-35 and 7-37 are wall temperatures at the cooling coils; the gas temperature in this region is considerably higher.

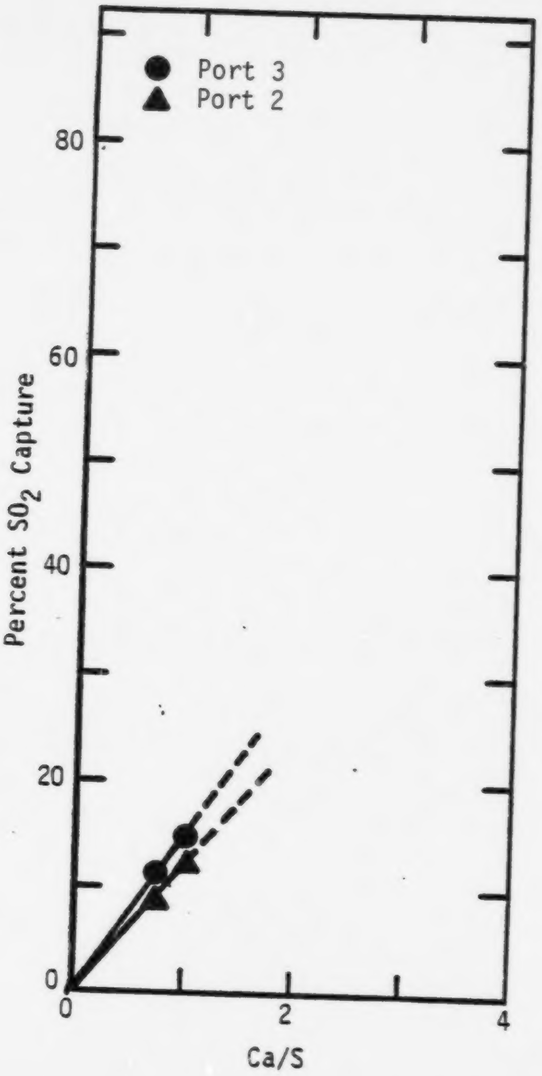
The data plotted in Figure 7-34 show the effect of sorbent type on sulfur capture for the uncooled, Indiana 3 coal fired conditions. The dolomite gave considerably better capture than the other sorbents under these conditions. Also, the smaller particle size, cleaner, Michigan marl gave



Fuel: Indiana 3
Staging: External
Cooling: None
Sorbent Loc.: With Staging Air
SO_2:

Load: 1.06 M Btu/hr
Run: 6-16
Ca/S: Shown
Sorbent: Vicron 45-3
SRp: 0.19
SR_1: 0.91
SR_T: 1.18-1.19

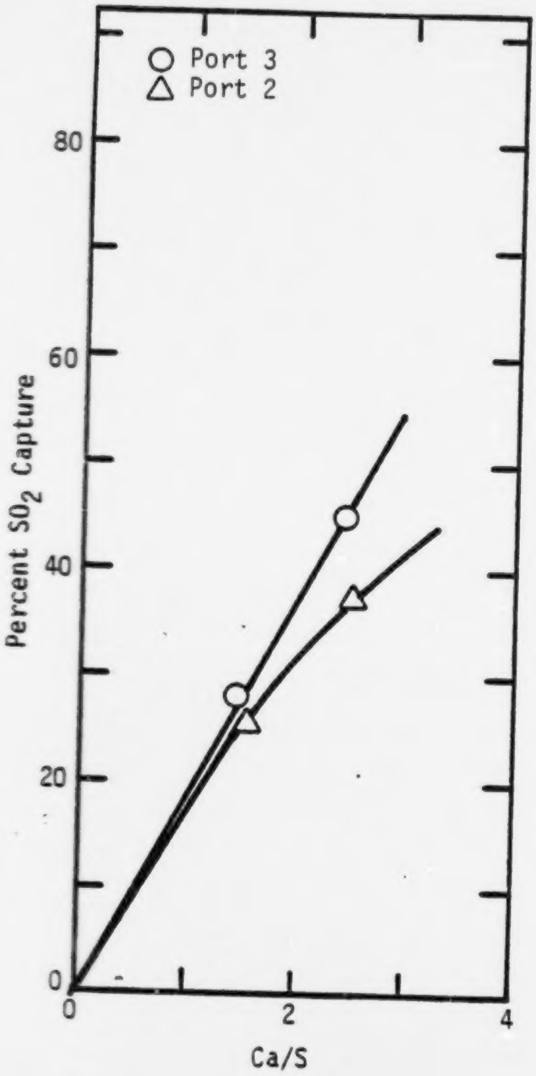
Figure 7-29. Sulfur capture for Vicron 45-3, externally staged sorbent in the staging air.



Fuel: Indiana 3
Staging: External
Cooling: None
Sorbent Loc.: With Staging Air
SO_2:

Load: 1.08-1.11 M Btu/hr
Run: 6-18
Ca/S: Shown
Sorbent: Vicron 15-15
SR_P: 0.20
SR_1: 0.90-0.91
SR_T: 1.19-1.20

Figure 7-30. Sulfur capture for Vicron 15-15, externally staged, sorbent with staging air.

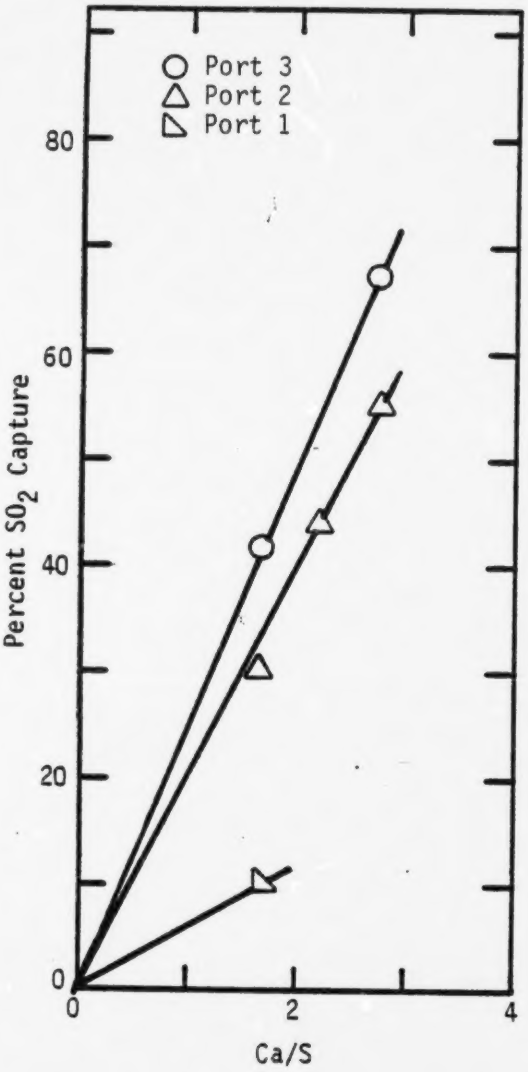


Fuel: Indiana 3
Staging: External
Cooling: None
Sorbent Loc.:With Staging

SO_2:

Load: 1.05-1.07 M Btu/hr
Run: 6-16
Ca/S: Shown
Sorbent: Michigan marl <200 mesh
SRp: 0.19-0.20
SR_1: 0.89-0.91
SR_T: 1.17-1.20

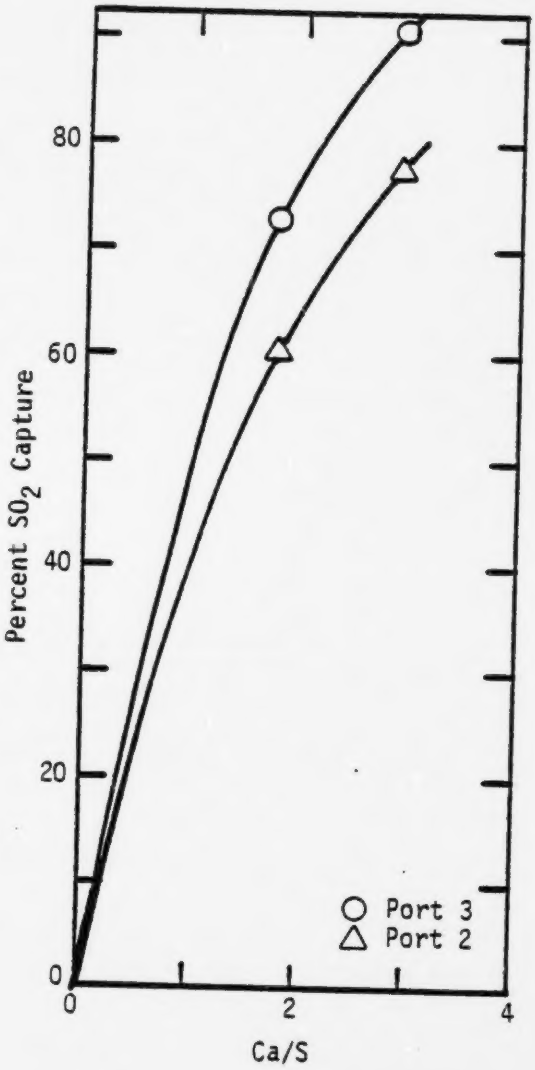
Figure 7-31. Sulfur capture for Michigan marl <200 mesh, externally staged, sorbent in staging air.



Fuel: Indiana 3
Staging: External
Cooling: None
Sorbent Loc.: With Staging Air
SO_2:

Load: 1.06-1.07 M Btu/hr
Run: 6-15
Ca/S: Shown
Sorbent: $Ca(OH)_2$
SRp: 0.19-0.20
SR_1: 0.88-.92
SR_T: 1.17-1.21

Figure 7-32. Sulfur capture for hydrated lime, externally staged sorbent in staging air.



Fuel: Indiana 3
Staging: External
Cooling: None
Sorbent Loc.: With Staging Air
SO_2:

Load: 1.06 M Btu/hr
Run: 6-16
Ca/S: Shown
Sorbent: Dolomite
SRp: 0.19-0.20
SR_1: 0.09-0.91
SR_T: 1.17-1.19

Figure 7-33. Sulfur capture for dolomite, externally staged, sorbent in staging air.

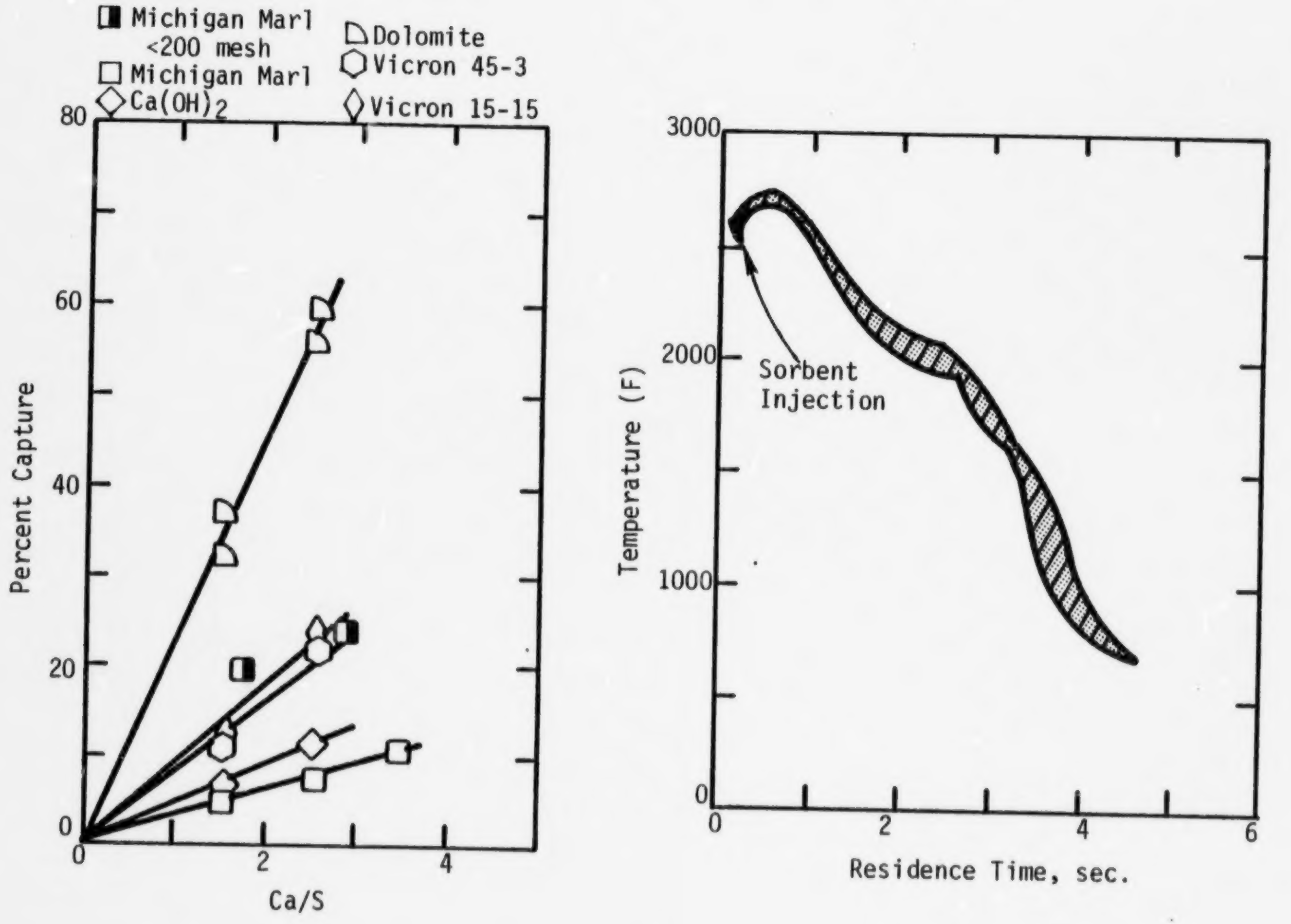


Figure 7-34. Thermal environment and effect of sorbent type on sulfur capture: Indiana 3 coal fired, uncooled, internally staged conditions, sorbent with fuel.

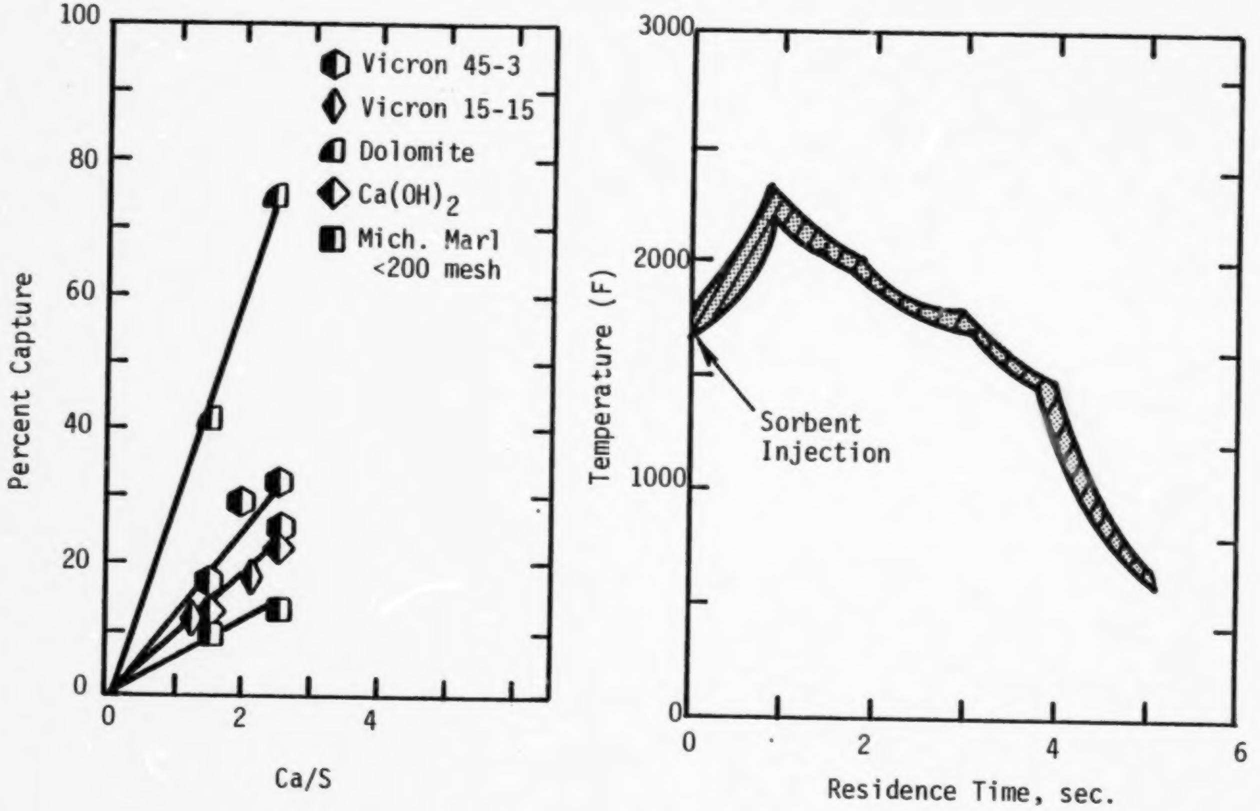


Figure 7-35. Thermal history and effect of sorbent on sulfur capture: Indiana 3 coal fired, cooled, sorbent with fuel, internally staged.

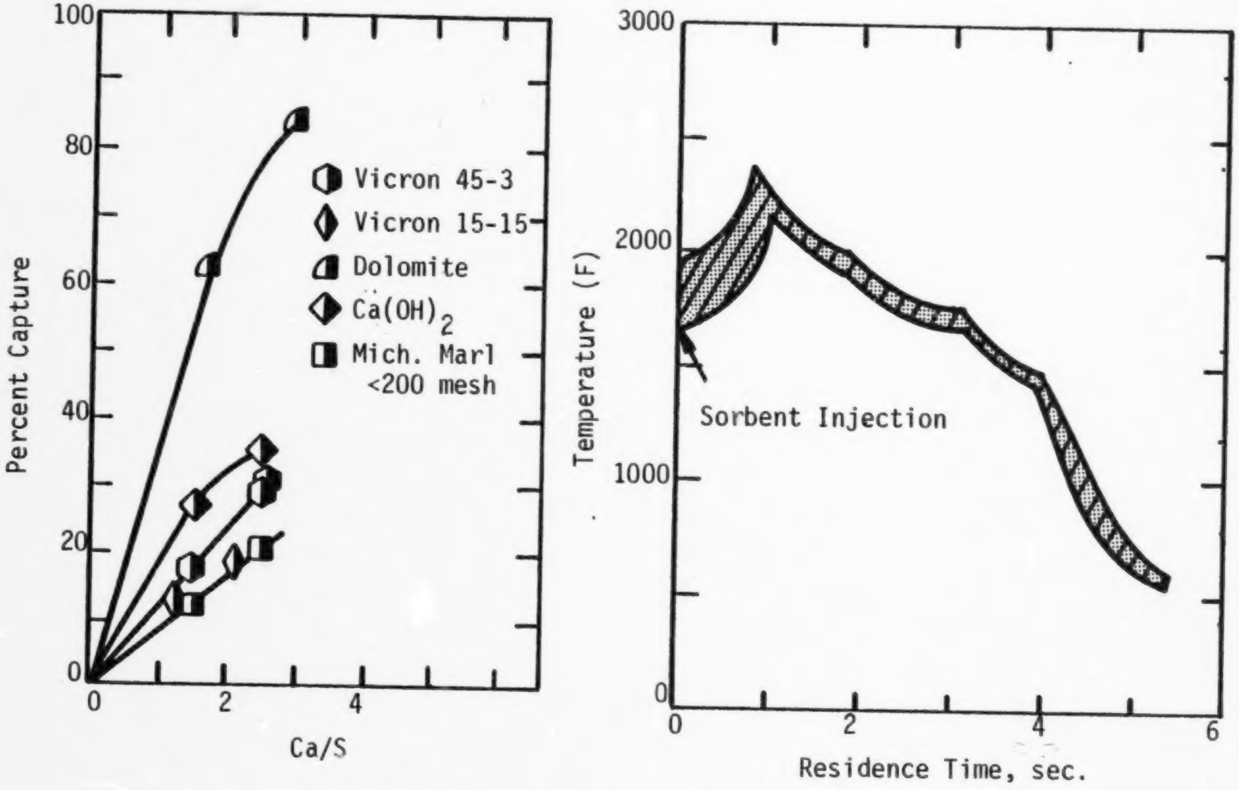


Figure 7-36. Thermal history and effect of sorbent type on sulfur capture: for Indiana 3 coal fired, sorbent with tertiary air, cooled, internally staged.

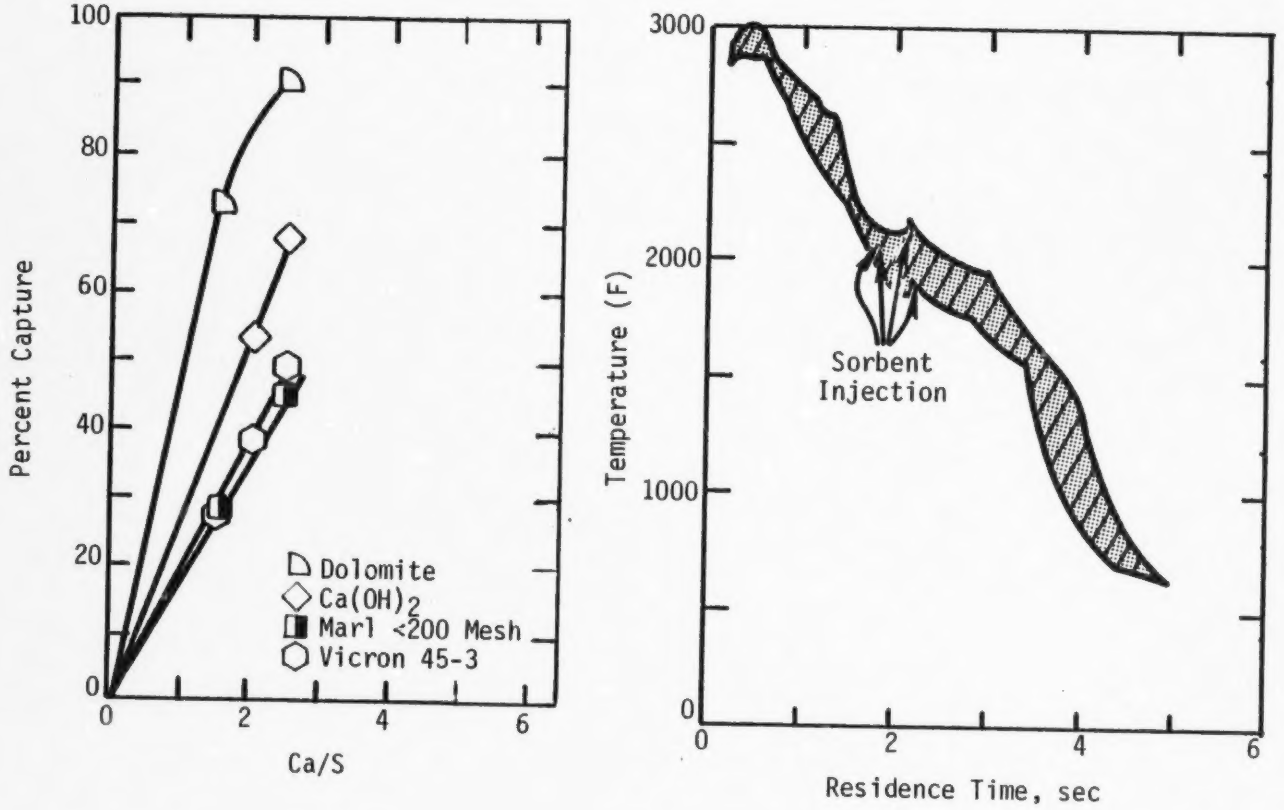


Figure 7-37. Thermal environment and effect of sorbent type on sulfur capture: Indiana 3 coal fired, externally staged, sorbent with staging air.

better capture than the original batch of marl. The improved performance of the cleaned, smaller sized, Michigan marl was expected but the good performance of the dolomite was surprising and cannot yet be explained.

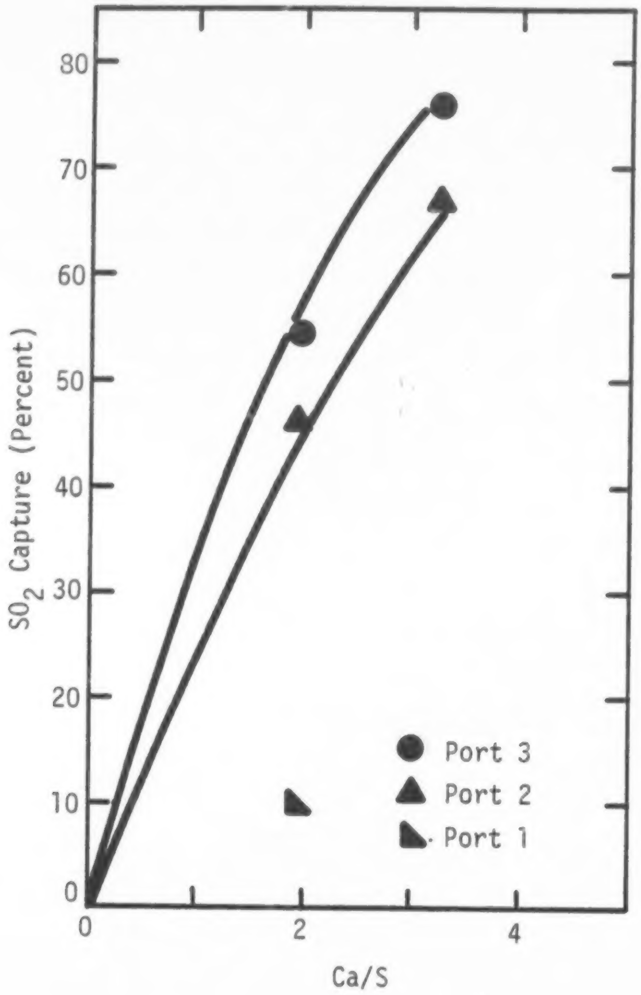
The effect of sorbent type on sulfur capture under cooled conditions, sorbent with the fuel, is shown by the data plotted in Figure 7-35. The variation in thermal environment for the series of tests is also shown. Cooling improved sorbent utilization for all the sorbents. Again the dolomite gave considerably better sulfur capture than the other sorbents. The data in Figure 7-36 show the effect of sorbent type on sulfur capture when the sorbent was injected with the tertiary air under Indiana 3 coal fired, cooled, conditions. The range of thermal environment for the test series is also shown. Again dolomite gave the best sulfur capture.

The performance of the calcium hydroxide (slaked lime) under three conditions (uncooled, cooled with fuel, cooled with T.A.) is notable. Earlier investigations (Payne et al, 1982) and other investigations (Flament, 1981 and Hein, 1981) have shown that hydrated lime, $Ca(OH)_2$, gave better capture than calcium carbonate, $CaCO_3$. This set of investigations shows that the relative performance of the two sorbents is a function of the experimental conditions, especially the thermal history of the sorbent. Under uncooled and cooled conditions the carbonate performed as well or better than the hydroxide when added with the fuel. When added with the tertiary air under cooled conditions the hydroxide gave better capture. It appears that the sulfur capture characterisrics of the hydroxide are more sensitive than the carbonate to the range of thermal histories provided by these experiments.

The data plotted in Figure 7-37 show the effect of sorbent type under externally staged coal-fired conditions. The furnace was uncooled, sorbent was added to the staging air. The range of furnace temperature is shown. The sorbent injection location, in terms of residence time, is also indicated. All of the sorbents exhibited higher performance for these conditions than for internally staged, uncooled conditions. Again, the dolomite gave the highest capture and the hydroxide was a better sulfur sorbent than the carbonate. It should be recalled that the sorbent was injected downstream of of the radiant furnace and, therefore, did not experience the peak temperatures in the system. It is not clear if the lower injection temperature is responsible for the improved performance or if the internally staged firing scheme creates conditions which deactivate the sorbent in some more subtle manner. There has been little evidence for deadburning of the sorbent encountered in any of the experiments performed.

The next set of figures show sulfur capture for the five sorbents using propane doped with H_2S as the fuel. The propane was fired with the "DMB" and the sorbent was added with air (the "primary" air) in an annulus immediately around the fuel nozzle. There was no cooling in the furnace for these tests. The fuel was doped with H_2S to approximately 2500 ppm SO_2 at the furnace exit. Figures 7-38 through 7-43 show data obtained for these conditions with all five sorbents. The sulfur capture for all of the sorbents was considerably higher than when fired under the same burner conditions with Indiana 3 coal. The difference in sulfur capture for the two fuels was most dramatic for the two Vicron sorbents. Sorbent utilization changed from ~ 10 percent to ~ 33 percent for the 45-3. The overall increase in sorbent utilization was greater than the increase in utilization for the Indiana coal due to cooling in the radiant furnace. However, the sulfur capture in the radiant furnace was a significantly smaller fraction of the overall utilization for the propane fired conditions than for the coal-fired, cooled conditions. It is not at all clear what difference in propane and coal firing is the cause of the observed change in sulfur capture. The effect of sorbent type on sulfur capture is summarized, along with the thermal characteristics of the system, in Figure 7-44. The sulfur capture of all of the sorbents was high with propane firing. Unlike the Indiana coal fired conditions, the dolomite and the two Vicrons exhibited essentially the same performance. Contrary to earlier studies (Hein, 1981, Flament, 1981) the hydroxide was not as effective as the carbonate. Moreover, the Michigan marl, which performed better than the carbonate in earlier pilot scale studies, was also worse than the carbonates or dolomite.

As was described earlier there are some measurements of sorbent characteristics which may be used to indicate the degree of deadburning, and therefore, the reactivity of the sorbent. In particular, the rate of dissociation of the sorbent in water and the hydration weight gain of a

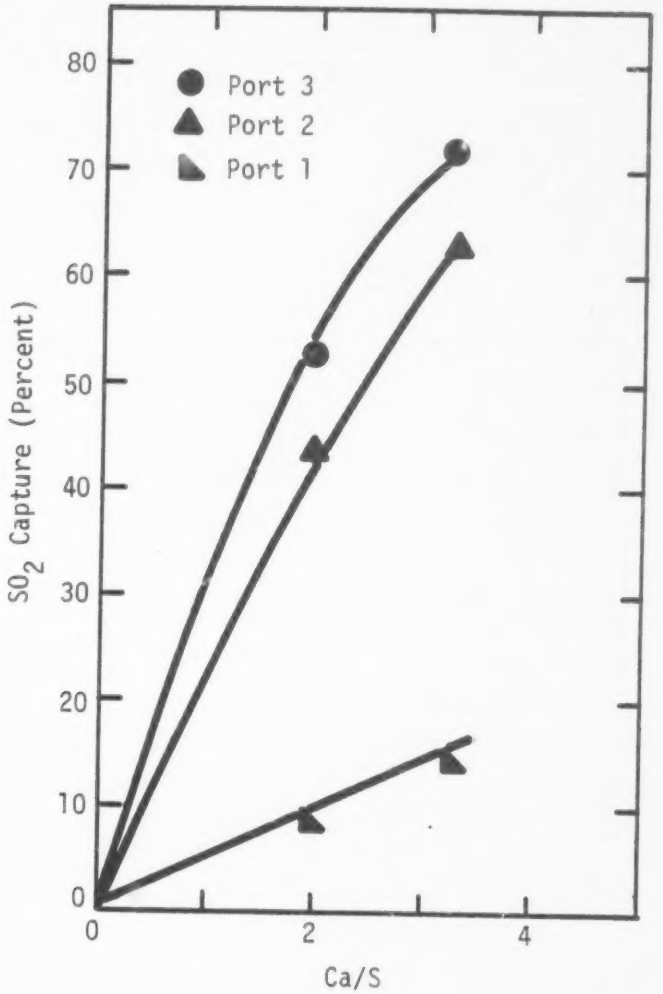


Fuel: Propane
Staging: Internal
Cooling: None
Sorbent Loc.: With Fuel

SO_2:

Load: 1.05 M Btu/hr
Run: 5-25, 1-4
Ca/S: Shown
Sorbent: Vicron 45-3
SR_p: 0.12
SR_b: 0.59-0.60
SR_T: 1.16-1.17

Figure 7-38. Sulfur capture for Vicron 45-3, propane fired, internally staged.

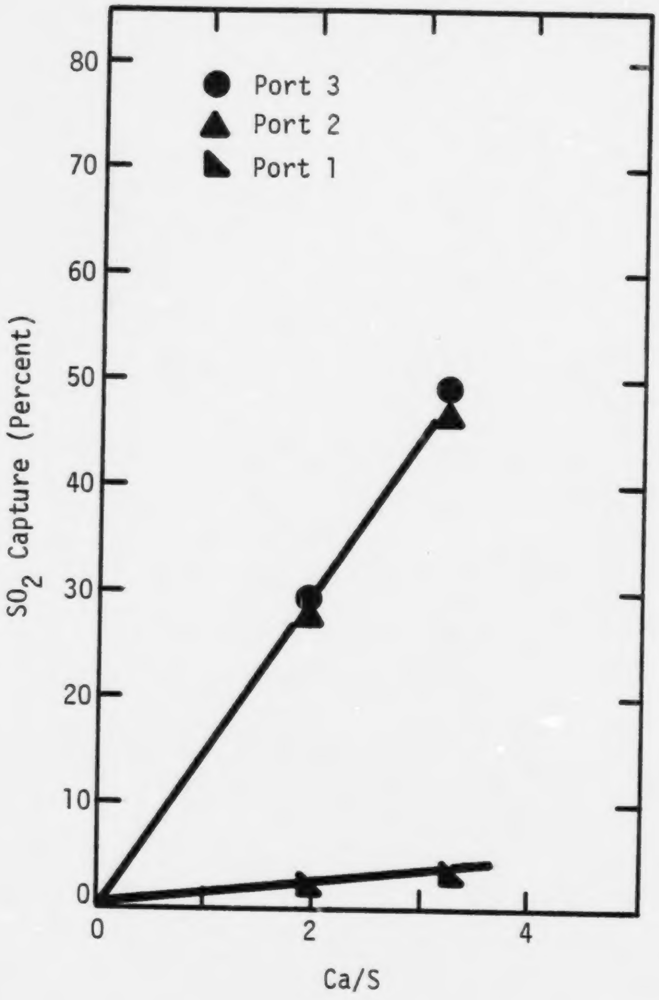


Fuel: Propane + H_2S
Staging: Internal
Cooling: None
Sorbent Loc.: With Fuel

SO_2:

Load: 1.02 MBtu/hr
Run: 5-19-1,4
Ca/S: Shown
Sorbent: Vicron 15-15
SRp: 0.12
SR_b: 0.59-0.61
SR_T: 1.12-1.17

Figure 7-39. Sulfur capture for Vicron 15-15, propane fired, internally staged.

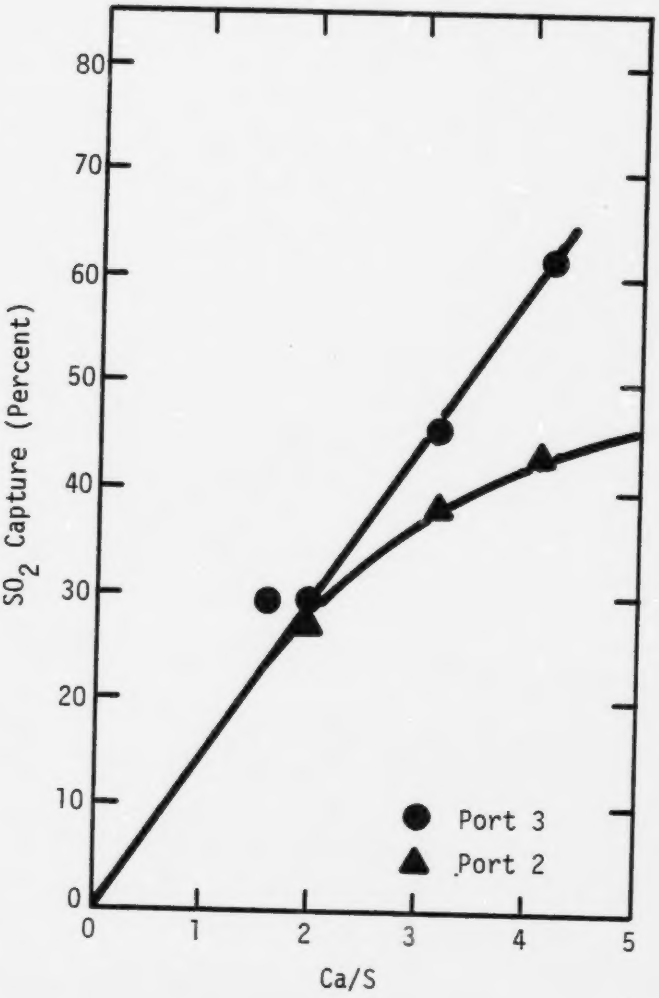


Fuel: Propane + H_2S
Staging: Internal
Cooling: None
Sorbent Loc.: With Fuel

SO_2:

Load: 1.01-1.03 M Btu/hr
Run: 5-21
Ca/S: Shown
Sorbent: Michigan marl
SRp: 0.12-0.13
SR_b: 0.57-0.60
SR_T: 1.15-1.18

Figure 7-40. Sulfur capture for Michigan marl, propane fired, internally staged.

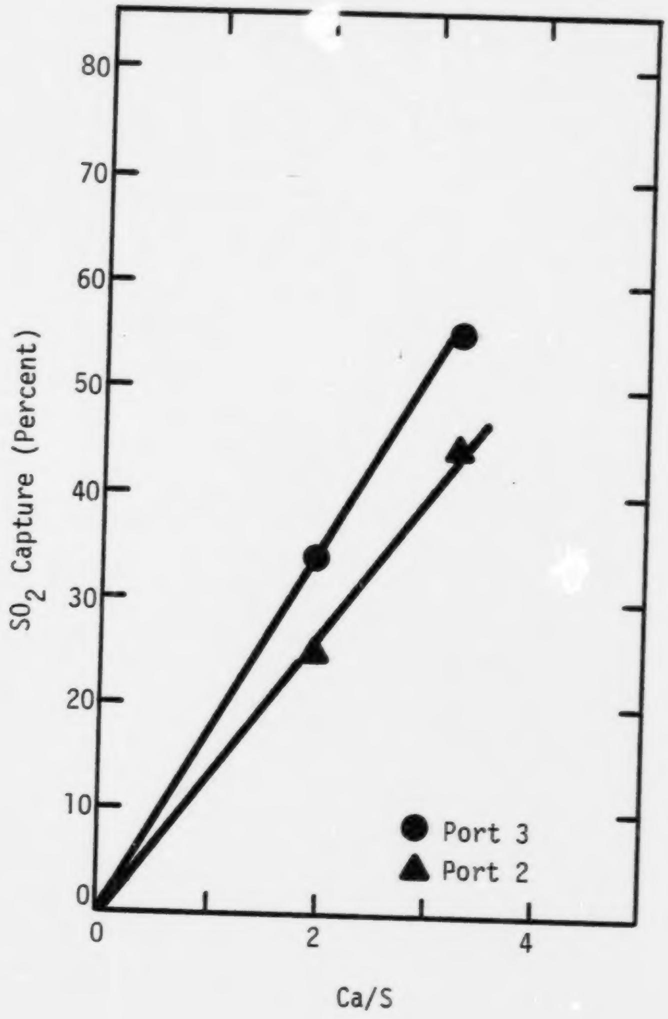


Fuel: Propane + H_2S
Staging: Internal
Cooling: None
Sorbent Loc.: With Fuel

SO_2:

Load: 1.05 MBtu/hr
Run: 6-21
Ca/S: Shown
Sorbent: Michigan marl <200 mesh
SRp: 0.11
SR_b: 0.59
SR_T: 1.22

Figure 7-41. Sulfur capture for Michigan marl <200 mesh, propane fired, internally staged.

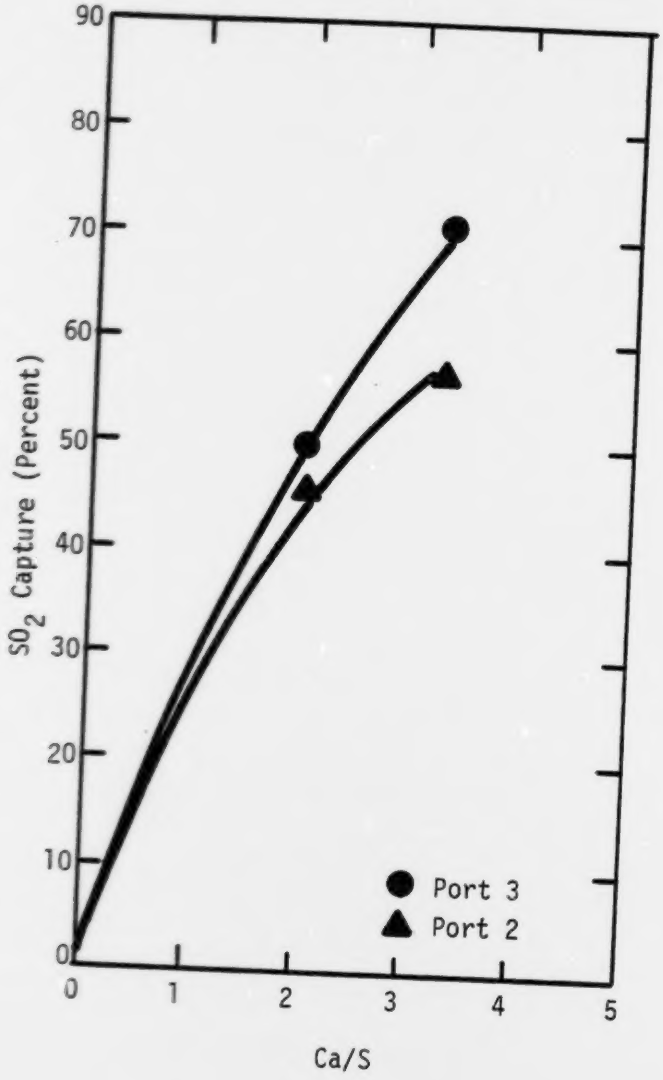


Fuel: Propane + H_2S
Staging: Internal
Cooling: None
Sorbent Loc.: With Fuel

SO_2:

Load: 1.02-1.04 MBtu/hr
Run: 5-20-1,4
Ca/S: Shown
Sorbent: $Ca(OH)_2$
SRp: 0.12
SR_b: 0.58-0.60
SR_T: 1.15-1.18

Figure 7-42. Sulfur capture for hydrated lime $Ca(OH)_2$, propane fired, internally staged.



Fuel: Propane/H_2S
Staging: Internal
Cooling: None
Sorbent Loc.: With Fuel

Load: 1.03-1.04 MBtu/hr
Run: 5-18, 1-4
Ca/S: Shown
Sorbent: Dolomite
SR_p: 0.12
SR_b: 0.59-0.60
SR_T: 1.17-1.19

Figure 7-43. Sulfur capture for dolomite, propane fired, internally staged.

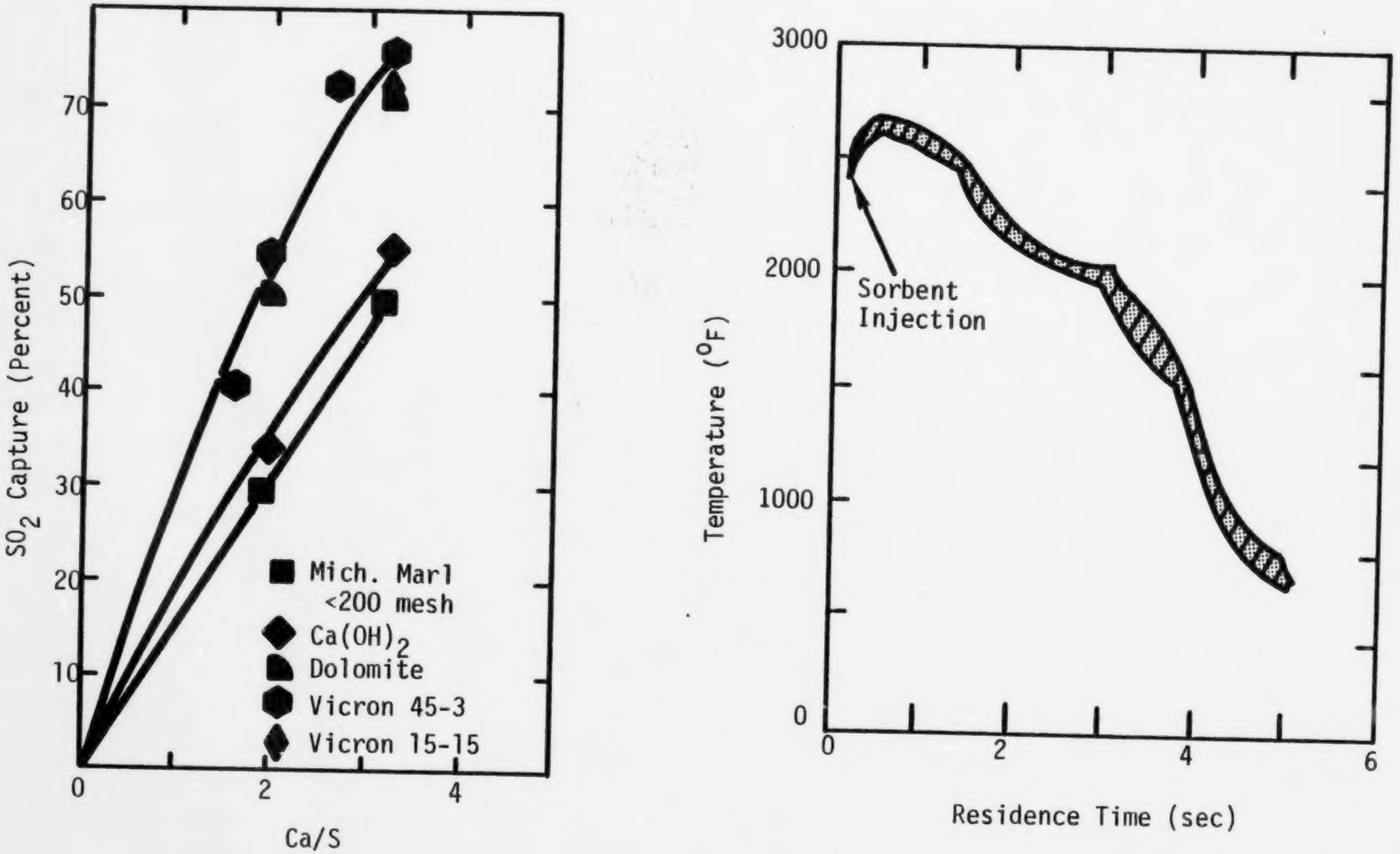


Figure 7-44. Effect of sorbent type on sulfur capture and basic thermal environment for propane-fired uncooled, internally staged conditions.

sorbent may be used to indicate reactivity of a sorbent relative to standard calcines of the same sorbent. In order to better characterize the sorbents, and to investigate the effect of the propane flame on the sorbents, solid samples were taken from two locations in the furance. The solid samples were taken without H_2S addition to the propane so that the rate of calcined sorbent (sorbent which had passed through the flame) dissolution could be measured. Figures 7-45 through 7-48 may be used to compare the characteristics of these flame calcined samples with the standard calcines of the same sorbents (reported earlier). The figures show sorbent dissolution rate for grab samples taken from the exit of the radiant furnace and the exit of the postflame cavity. Sample surface area, calcium content, and hydration weight gain are also summarized. The percent utilizations reported are for the H_2S doped conditions run before these samples were obtained. There is no flame calcined sample of the Vicron 45-3 because of operational problems during the run.

The relationship between the measured properties of the flame and standard calcines and the overall sorbent utilization is not clear. More work should be done on the development of methods for the measurement of sorbent reactivity.

7.2 Results, Fuel Effects (Series C-2)

There has been little systematic investigation of the effect of fuel type on sulfur capture. Evidence has been presented by several investigators on the effect of the gaseous sulfur species concentration on sulfur capture. Some work relating ash composition with inherent sulfur capture has also been published. Fuel type may affect sulfur capture because the adiabatic flame temperature (and thus the maximum possible sorbent temperature) and the sulfur evolution pattern of a fuel is fuel type and composition dependent. Four fuels were chosen for the fuel effect screening study including:

- Indiana 3 - the baseline medium-sulfur bituminous coal.
- Propane doped with H_2S - eliminating the complication of sulfur evolution from the solid.

Run Conditions (no sulfur added)
Date 5-19-82 Sorbent Vicron 15-15
Fuel Propane SR_b .61 SR_T 1.19 Load 1.02
Sorbent location with fuel % Utilization (total) 22

Sorbent Characteristics

Location	Input	□ Exit Rad.	■ Exit P.F.C.
% Ca	39.3	46.6	48.8
Surface area m^2/gm	2.73	3.85	3.70
% weight gain		26.5	28.4

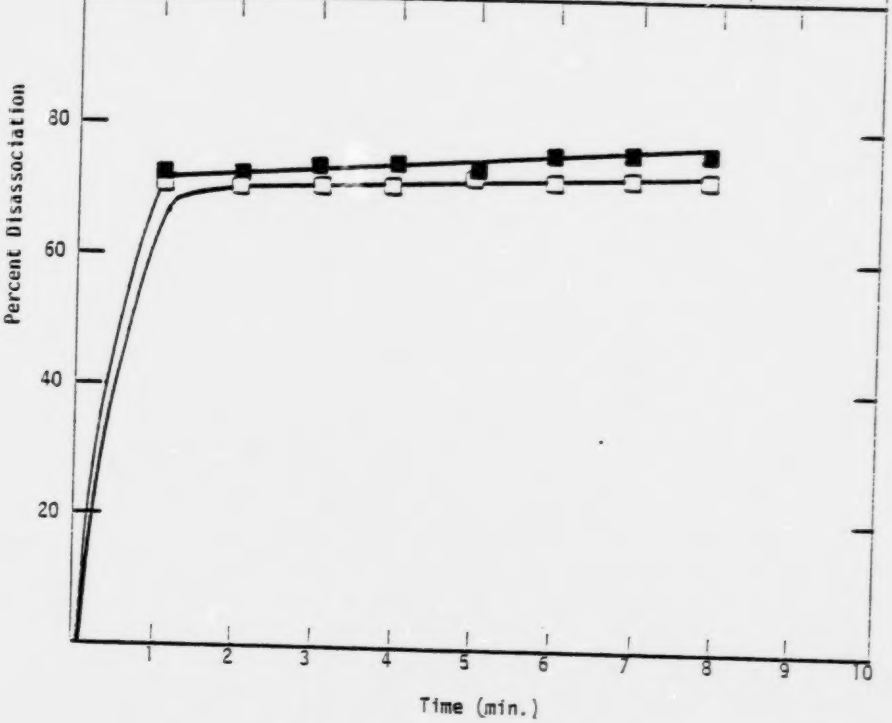


Figure 7-45. Reactivity of sorbent subjected to propane flame (no sulfur present) Vicron 15-15.

Run Conditions (no sulfur added)

Date 5/21/82 Sorbent Michigan Marl (All)
Fuel Propane SR_b 0.59 SR_T 1.17 Load 1.03 M Btu/hr
Sorbent location with fuel % Utilization (total) 14

Sorbent Characteristics		☐	■
Location	Input	Exit Rad.	Exit P.F.C
% Ca	25.2	44.8	43.0
Surface area m^2/gm		1.72	1.30
% weight gain		26.4	28.4

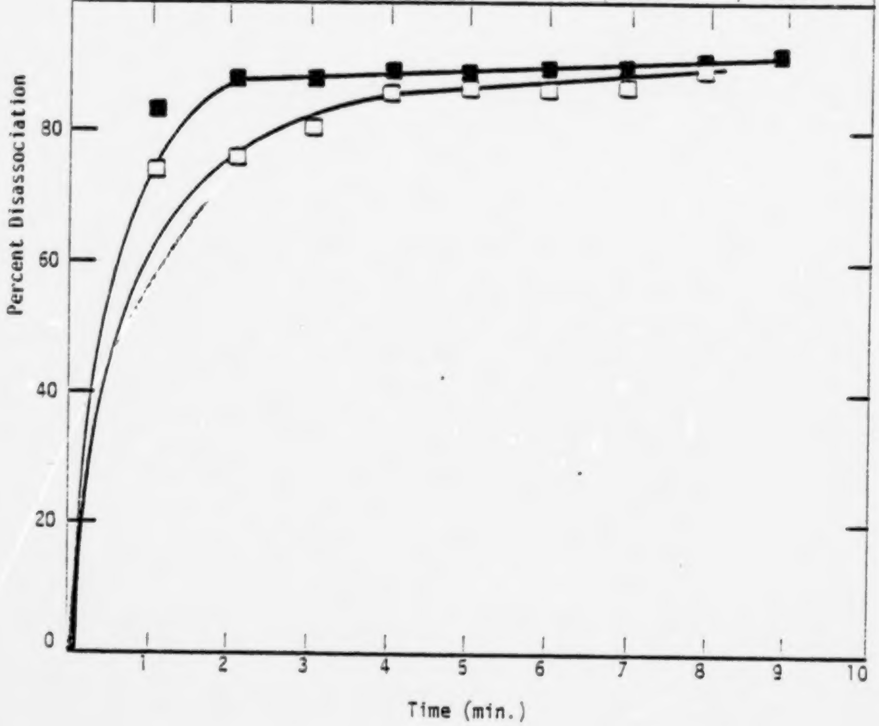


Figure 7-46. Reactivity of sorbent subjected to propane firing (no sulfur present) Michigan marl, all size fractions.

Run Conditions (no sulfur added)
Date 5-20-82 Sorbent $Ca(OH)_2$
Fuel Propane SR_b .60 SR_T 1.18 Load 1.03 M Btu/hr
Sorbent location with fuel % Utilization (total) 16

Sorbent Characteristics		☐	■
Location	Input	Exit Rad.	Exit P.F.C.
% Ca	26.4	52.3	32.0
Surface area (m^2/gm)	10.7	2.05	2.38
% weight gain		29.4	31.0

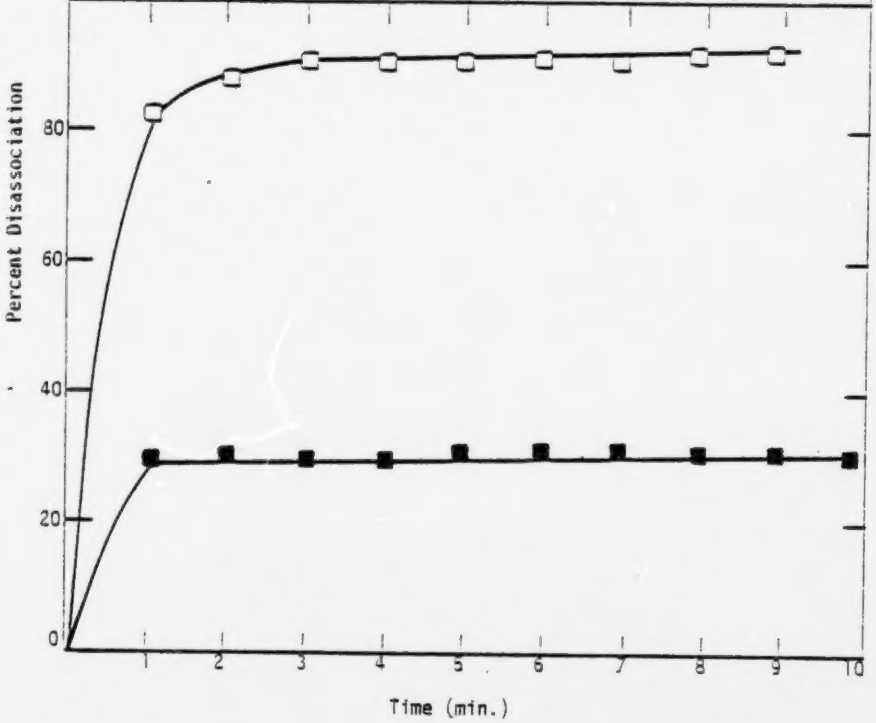


Figure 7-47. Reactivity of sorbent subjected to propane firing (no sulfur present), $Ca(OH)_2$.

Run Conditions (no sulfur added)

Date: 5-18-82 Sorbent: Dolomite

Fuel: Propane SR_b .60 SR_T 1.19 Load 1.03 M Btu/hr

Sorbent location with fuel % Utilization (total) 22-25

Sorbent Characteristics		☐	■
Location	Input	Exit Rad.	Exit P.F.C.
% Ca	21.0	34.2	30.6
Surface area (m^2/gm)	0.64	2.85	3.33
% weight gain		42.8	36.5

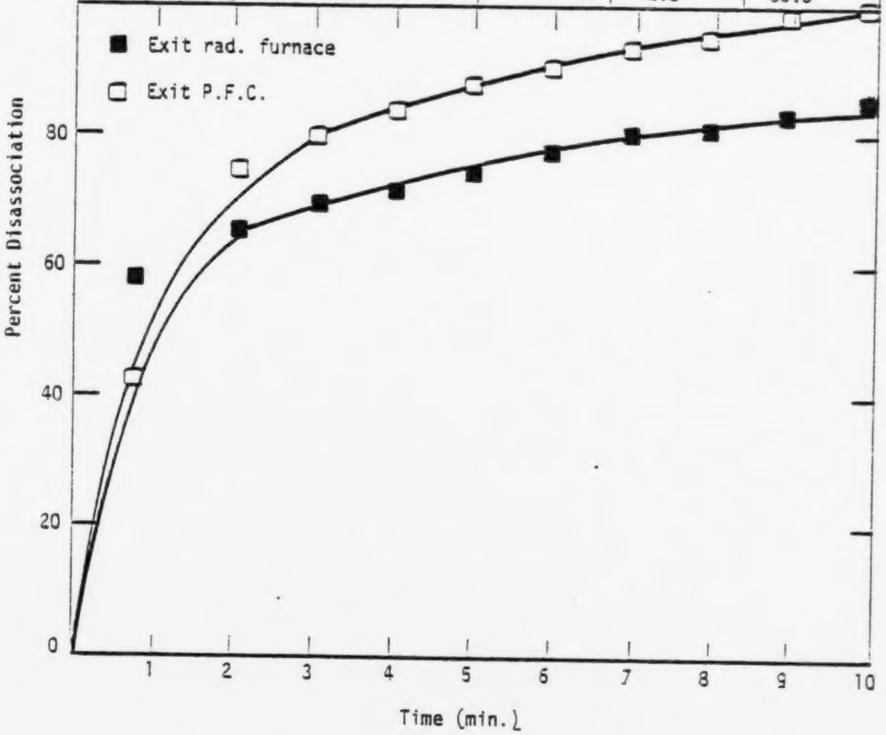


Figure 7-48. Reactivity of sorbent subjected to propane firing (no sulfur present), Dolomite.

- Beulah - a low-sulfur North Dakota lignite
- CWS - a coal/water slurry made from a metalurgical coal slurred with a minimum (~ 25 percent) of water.

The compositions, proximate and ultimate analyses of these fuels is shown in Table 7-4. All of the fuels were fired with the internally staged (DMB) burner at full load without cooling. All of the sorbents were tested with both the Indiana 3 coal and propane/H_2S as discussed in Section 7.2. The other fuels were tested only with Vicron 45-3.

Data from the fuel effects studies are shown in Figure 7-49. The data are plotted as a function of $\sqrt{SO_2} \times Ca/S$ because the sulfur content of the fuels varied. Figure 7-50 shows the measured thermal history of the BSF when firing the four fuels. The temperatures shown are wall temperatures measured with thermocouples and residence times are based on plug flow calculations.

There was considerable variation in the Beulah coal fired. The first batch of coal was pulverized in the usual manner, using preheated air in the mill and classifier. The hot air removed a considerable amount of moisture from the coal (from 24.6 percent H_2O in the coal pile to 16 percent H_2O pulverized). A second batch of coal was ground. The mill air was not heated during the second grind and the coal produced contained 24.7 percent H_2O. Unfortunately, the sulfur content (dry basis) also changed, from 1.08 to 0.71. Figure 7-51 compares the data taken with the two Beulah coals normalized by the sulfur content. Essentially no difference in sulfur capture was observed.

It was not possible to add the sorbent with the fuel when firing the coal/water slurry. The sorbent was added with the tertiary air. The effect of sorbent location was tested with Beulah and with Indiana 3. Under staged conditions with either fuel the sorbent location had no effect (see Figure 7-52 and earlier, Indiana 3, fired data).

The fuel effects data indicate that some fuel difference, for example rate of heat release, peak temperature (in relation to sorbent injection

TABLE 7-4. FUEL CHARACTERISTICS

	Indiana 3 (As Used)	Beulah (As Used)	CWS (As Used)
Ultimate Analysis (%, Dry)			
Carbon	73.0	59.37	82.71
Hydrogen	4.8	4.64	5.39
Nitrogen	1.3	0.90	1.81
Sulfur	1.3	0.65	1.18
Oxygen	9.0	21.08	5.04
Ash	10.6	13.36	3.87
Moisture	3.2	20.1	20.4
Heating Value (Dry)	12,760	9,900	14,693
Percent Volatiles (Dry)	34.3	44.60	34.87
Ash Analysis			
SiO_2	57.5	41.5	28.4
Ai_2O_3	23.9	15.4	15.3
TiO_3	0.9	1.2	.70
Fe_2O_3	12.2	6.7	50.9
CaO	1.3	11.3	1.0
MgO	0.6	4.3	0.9
Na_2O	0.2	5.1	0.7
K_2O	1.2	1.4	1.1
P_2O_5	0.5	.6	.5
SO_3	0.7	11.6	1.0
Forms of Sulfur (Dry)			
Total	1.29	1.14	
Pyrite	0.58	0.53	
Organic	0.47	0.58	

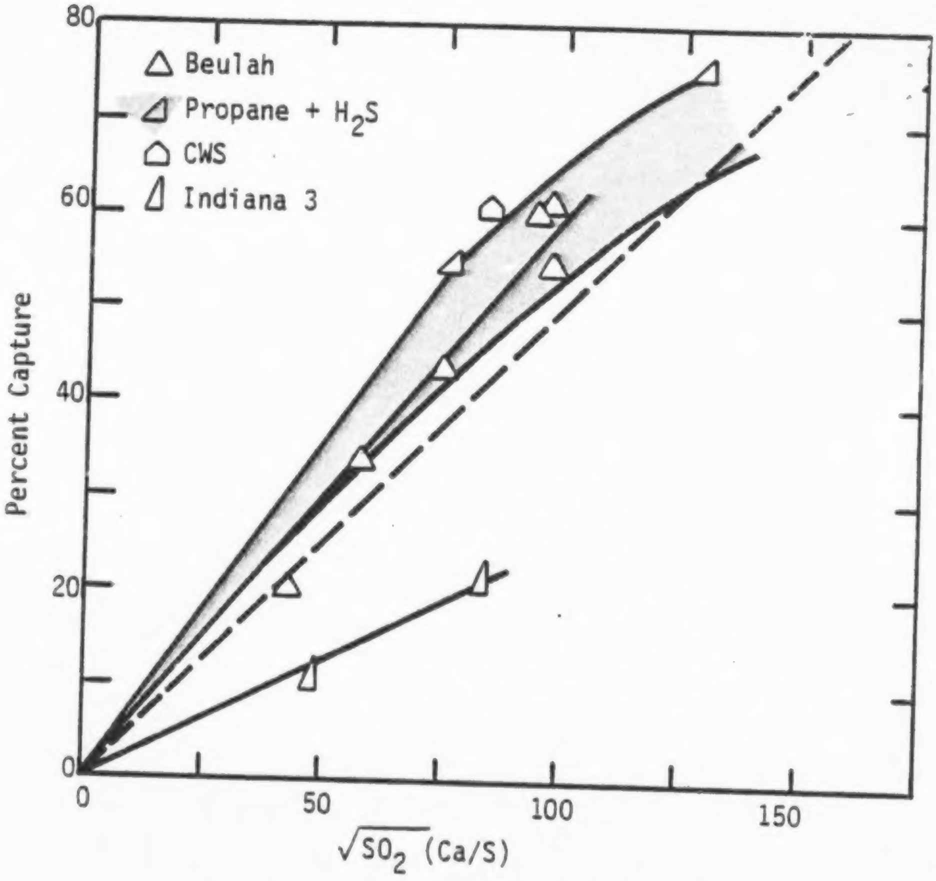


Figure 7-49. Effect of fuel on sulfur capture (Vicron 45-3).

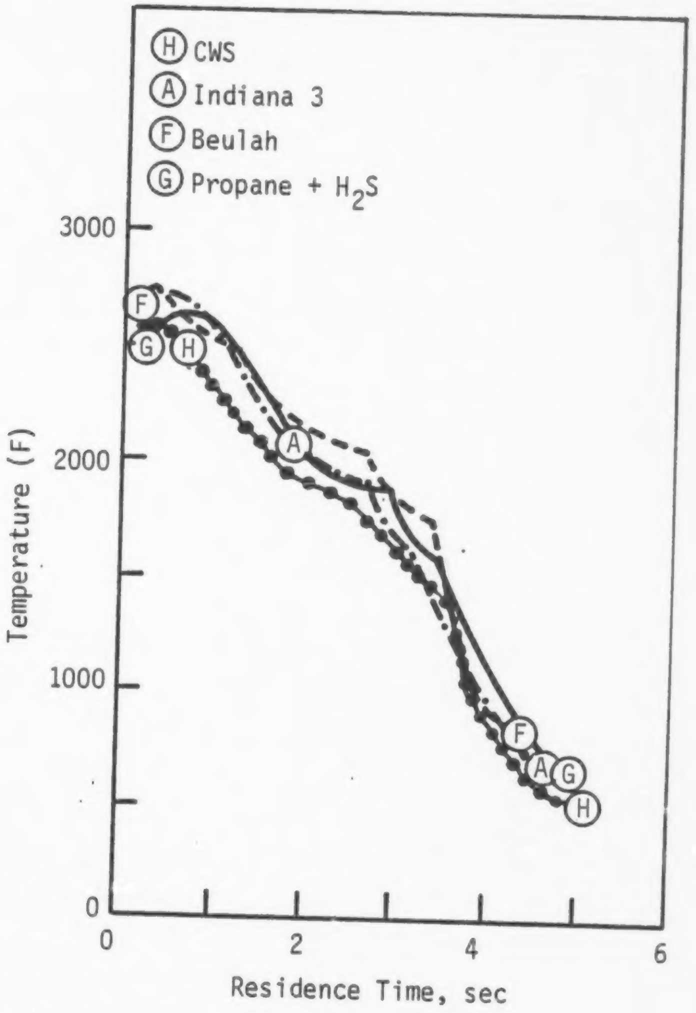


Figure 7-50. Effect of fuel on thermal history (wall temperature).

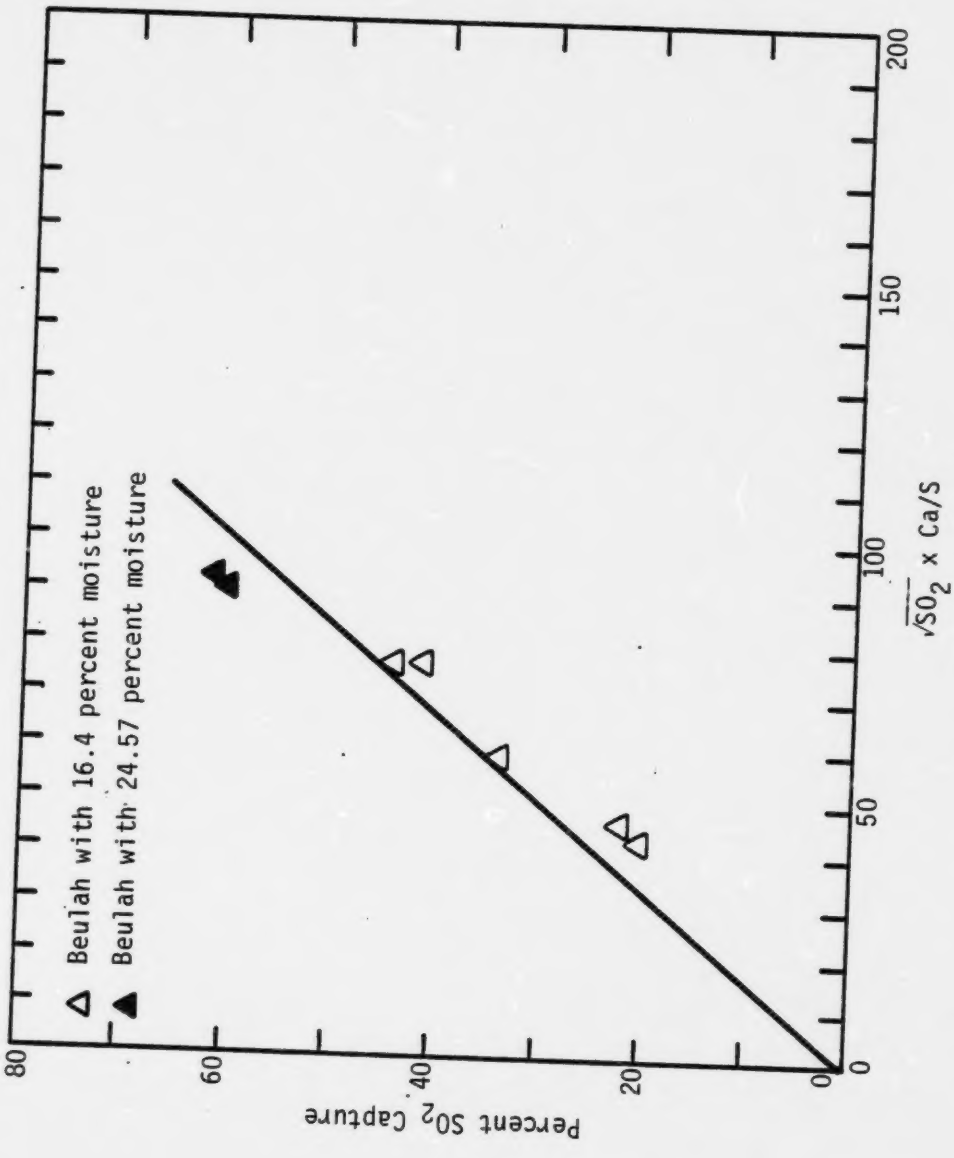


Figure 7-51. Effect of moisture content on sulfur capture, Beulah coal, uncooled.

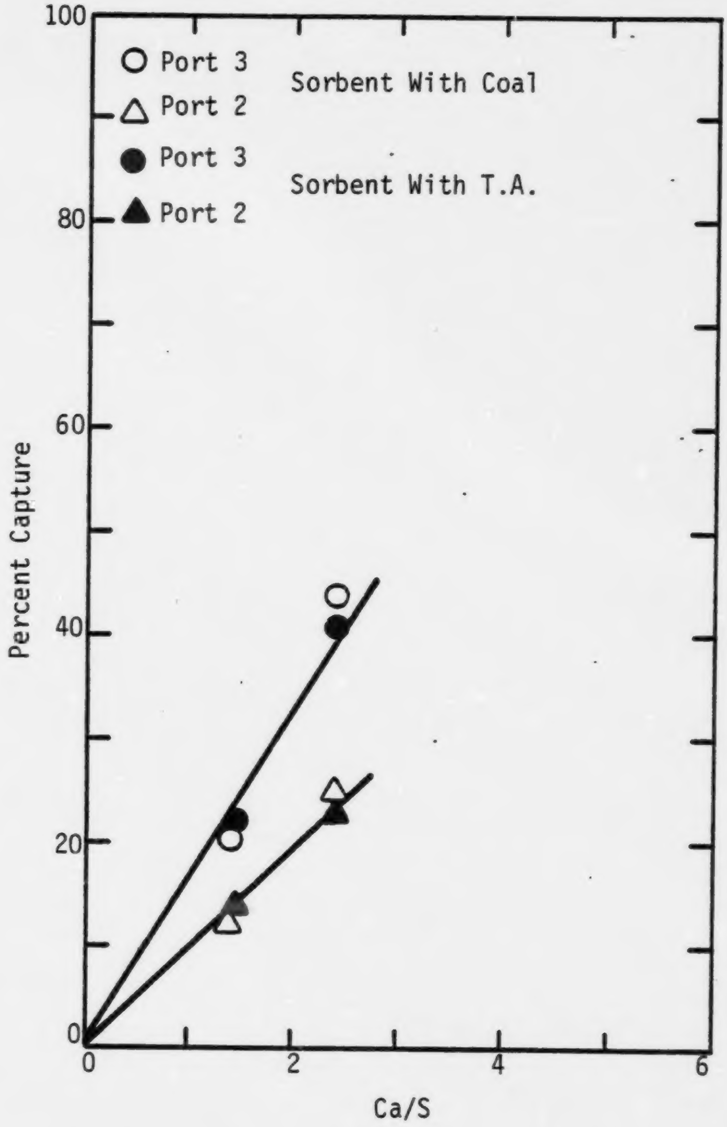


Figure 7-52. Effect of sorbent location on sulfur capture; Beulah coal, uncooled, internally staged.

velocity) or some compositional difference, has a strong impact on sulfur capture. It is not clear what this fuel factor is; wall temperature profiles are not sufficient to characterize fuel heat release patterns in the BSF, and there is no obvious chemical difference in the fuels which explains the observed effects.

To further characterize the fuel combustion properties, especially to indicate the limits of possible peak temperatures for the fuels, adiabatic flame temperature calculations were made. The calculations were based on the compositions and measured heating values listed in Table 7-3. The results of these calculations are shown in Figure 7-53.

7.3 Fuel and Sorbent Studies, Summary

The effect of sorbent type on sulfur capture at five combustion conditions was studied. Five sorbents: two size fractions of a high purity limestone (Vicron 45-3 and Vicron 15-15), a midwestern marl, a hydrated lime ($Ca(OH)_2$) and a midwestern dolomite were used. The sorbents were tested with: Indiana 3 coal fired with a distributed mixing burner cooled and uncooled; Indiana 3 coal, externally staged; and with propane doped with H_2S. The results of these tests have been described in detail and discussed. In general the dolomite gave good capture under all of the conditions examined. The hydrated lime appeared to be most sensitive and the dolomite least sensitive to the range of changes in thermal environment used. High captures with the propane/H_2S firing were observed for all of the sorbents; the reason for the difference in capture with Indiana coal and propane under similar operational conditions is not clear.

The effect of fuel on sulfur capture by Vicron 45-3 was also investigated. Four fuels were used: Indiana 3 coal, Beulah (a North Dakota lignite), propane doped with H_2S and a coal/water slurry. The furnace was fired with a distributed mixing burner and was not cooled. The Indiana 3 coal-fired condition gave considerably worse capture than the other fuels. Adiabatic flame temperatures were calculated for all the fuels at stoichiometric ratios from 0.6 to 1.2. The adiabatic flame temperatures of the solid fuels rank in the same order as the sulfur capture obtained (the

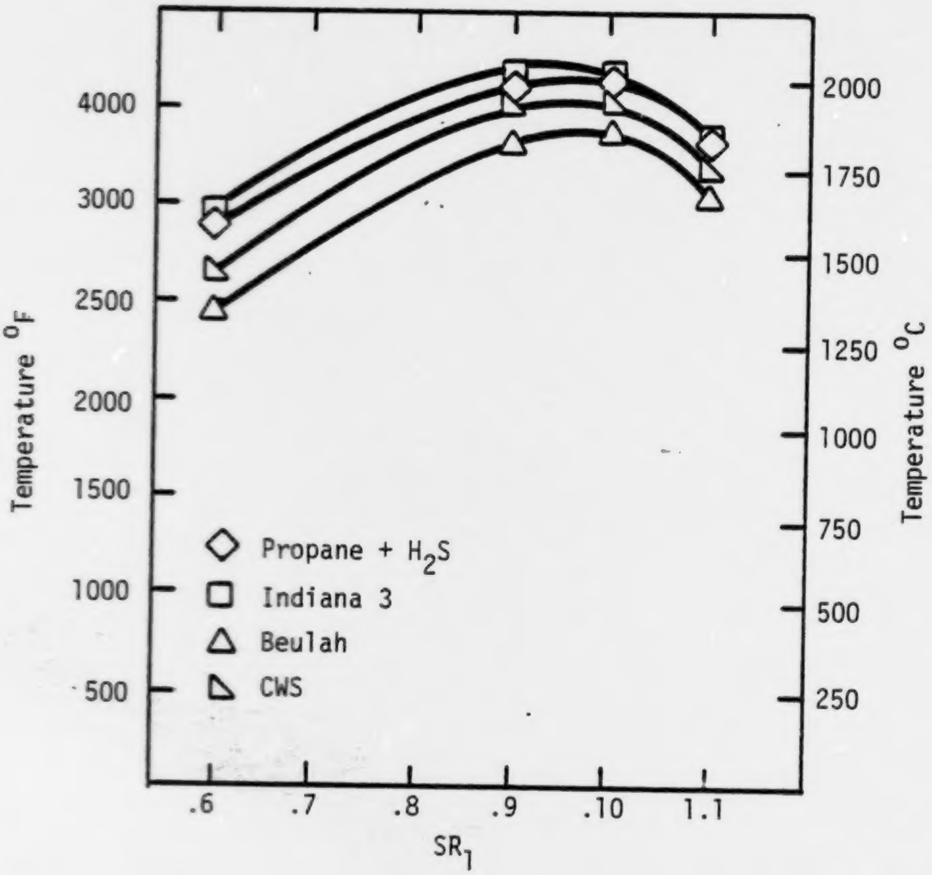


Figure 7-53. Calculated adiabatic flame temperatures.

highest temperature corresponding to the lowest sorbent utilization) but the differences in calculated temperatures are probably not sufficient to explain the differences in capture.

8.0 CONCLUSIONS

The results of the experimental studies conducted in the boiler simulator furnace indicated that the parameters of major importance were thermal environment, calcium to sulfur ratio, and sorbent composition. Thermal environment (local temperature) was shown to have a strong effect on the utilization of dry sorbents injected directly into the furnace. The burner staged experiments showed the influence of temperature most clearly; a reduction in peak flame temperature, due to cooling in the radiant zone or to a reduction in load, increased the sulfur capture significantly. Changes in other combustion parameters, such as sorbent location and injection velocity, had secondary effects on sulfur capture.

The effect of thermal history under physically staged conditions was less definitive. Changes in both load and thermal cooling in the radiant furnace were complicated by the changes in furnace temperature due to the physical staging itself, since physically staging the coal flame significantly altered the furnace temperature profile. With external staging near stoichiometric conditions, the first (fuel rich) stage, which included the entire radiant furnace, and the second stage region (the first part of the post flame cavity) were hotter than under burner-staged conditions. First stage stoichiometry and sorbent location both influenced sulfur capture under externally staged conditions; however, the results suggest that these influences may be more strongly related to thermal changes than to chemical changes. Further, the data do not support the concept that sorbent utilization is much higher under fuel rich conditions.

The influence of sorbent type on sulfur capture was studied at five different combustion conditions. Five sorbents were examined in these studies:

- Vicron 45-3
- Vicron 15-15
- Michigan Marl
- Hydrated Lime [$Ca(OH)_2$]
- Dolomite

These sorbents were tested with the Indiana three coal fired in the distributed mixing burner with and without external cooling, the Indiana three coal under externally staged conditions, propane doped with H_2S. In general, the Dolomite gave good capture under all conditions examined. The hydrated lime appeared to be most sensitive to thermal environment while the Dolomite was least sensitive to changes in thermal environment. High captures were observed for all of the sorbents when the primary fuel was propane/H_2S. The effect of fuel sulfur on sorbent utilization was investigated by studying: Indiana three coal, Beulah lignite (from North Dakota), propane doped with H_2S, and a coal/water slurry. All of the fuel screening tests were conducted with Vicron 45-3 as the sorbent and the boiler simulator furnace was fired with the distributed mixing burner and no additional cooling was added. The sorbent utilization was significantly less when the primary fuel was the Indiana coal than in all of the other cases tested. Adiabatic flame temperatures were calculated for all of the fuels at stoichiometric ratios from 0.6 to 1.2 and the calculated temperatures for the solid fuels rank in the same order as the sulfur capture obtained; the highest sorbent utilization was achieved with the fuel producing the lowest theoretical temperature. However, the differences in calculated temperature do not appear to be significant enough to explain the large differences in capture. The data strongly suggest that the difference between the relatively poor sorbent utilization with the Indiana coal and the excellent sorbent utilization with the propane/H_2S cannot be solely attributed to thermal effects.

REFERENCES

Flament, G., "The Simultaneous Reduction of NO_x and SO_x in Coal Flames by Direct Injection of Sorbents in a Staged Mixing Burner." International Flame Research Foundation (IFRF) Doc. No. G19/a/10, September, 1981.

Hein, K., and W. Glazer, "Dry Additive Process for SO_2 Removal During the Combustion of Brown Coals." Proc. Sixth Members' Conference IFRF, 1981.

Payne, R., P. L. Case, M. P. Heap, J. Lee, C. N. McKinnon, P. Nelson, D. W. Pershing, "Fourth Annual Report - Development of Criteria for Extension of Applicability of Low-Emission, High-Efficiency Coal Burners." EPA Contract 68-02-2667, October, 1982.

APPENDIX A

MEASUREMENTS

APPENDIX A

MEASUREMENTS

Measurements performed as part of this experimental program included:

- Gaseous species concentrations;
- Solids composition and physical characteristics;
- Furnace and gas temperatures.

Table A-1 summarizes the gas and solid species measured and the solid characteristics determined. The methods and instruments used for these measurements are listed, as are the probes and sample conditioning systems used to obtain samples. This section describes the standard sampling and analytical systems used for the bench scale studies, including the development and testing of a probe and sample conditioning system for sulfur species measurements.

A.1 Gas Samples

The measurement of sulfur species in combustion products containing active sorbents poses several special problems. Sulfur species are water soluble and highly reactive with calcium-based sorbents. It is imperative that gas-solid contacting be minimized and contact between the gas and any condensed water be avoided. Therefore, a phase "discrimination probe" for the measurement of sulfur species was designed, constructed and tested. The probe is designed so that the sulfur species sample is extracted from the main particle laden sample stream at right angles to the main flow and at a relatively low velocity (see Figure A-1). The probe supplies two gas streams simultaneously: the main, particle-laden stream which is used for continuous monitoring of O_2, CO, CO_2, NO_x and the side, nearly particle-free, stream which is used for SO_2 measurement. Sample conditioning for the two streams is somewhat different (see Figure A-2). The main sample (O_2, CO, CO_2, NO_x) is dried using an iced condenser, filtered, pressurized, filtered again and delivered to the continuous instrumentation listed in Table A-1. The SO_2 gas sample is transported in a heated teflon line maintained above 115 C under vacuum to a heated filter followed by a permeation tube drier. The permeation tube drier selectively removes water vapor from the gas sample. Dry air is used as the dry gas medium in the permeation drier. The sample is then pressurized and delivered to the analytical system (see Figure A-3). SO_2 concentration is

TABLE A-1. MEASUREMENTS

Measurement	Probe and Conditioning	Analytical Method/Instrument
Gases		
O_2	Standard or phase discrim. - Continuous	Paramagnetic (Taylor)
CO_2	"	Nondispersive infrared (Anarad)
CO	"	"
NO_x	"	Chemiluminescent (TECO)
SO_2	Phase discrimination, continuous or batch	Nondispersive ultraviolet (DuPont) or GC (as below)
H_2S	phase discrimination or gas stream from solids	Gas chromatograph with flame--photometric detector
COS	"	"
CS_2	"	"
Temperatures		
Furnace temp.	Wall thermocouples	Type S or K thermocouples
Gas temp.	Suction pyrometer	Type S thermocouple
Solids		
Mass loading	Isokin. solids probe	Mass basis, ash as tracer
Carbon	" " " or grab sample with	CO_2 evolution, combustion (Perkin-Elmer 240B)
Hydrogen	glass cyclone	H_2O evolution "
Nitrogen	"	N_2 evolution "
Oxygen	"	Difference (total - [C+H+N+S + ash])
Sulfur	"	SO_2 evolution (Leco)
Ash	"	Combustion
Heating value	"	Astm
CaO	"	
Size distrib.	"	Sedimentation
Surface area	"	N_2 adsorption BET (Quantachrome)
Hydration weight gain	"	H_2O uptake
Dissolution rate	"	Acid titration

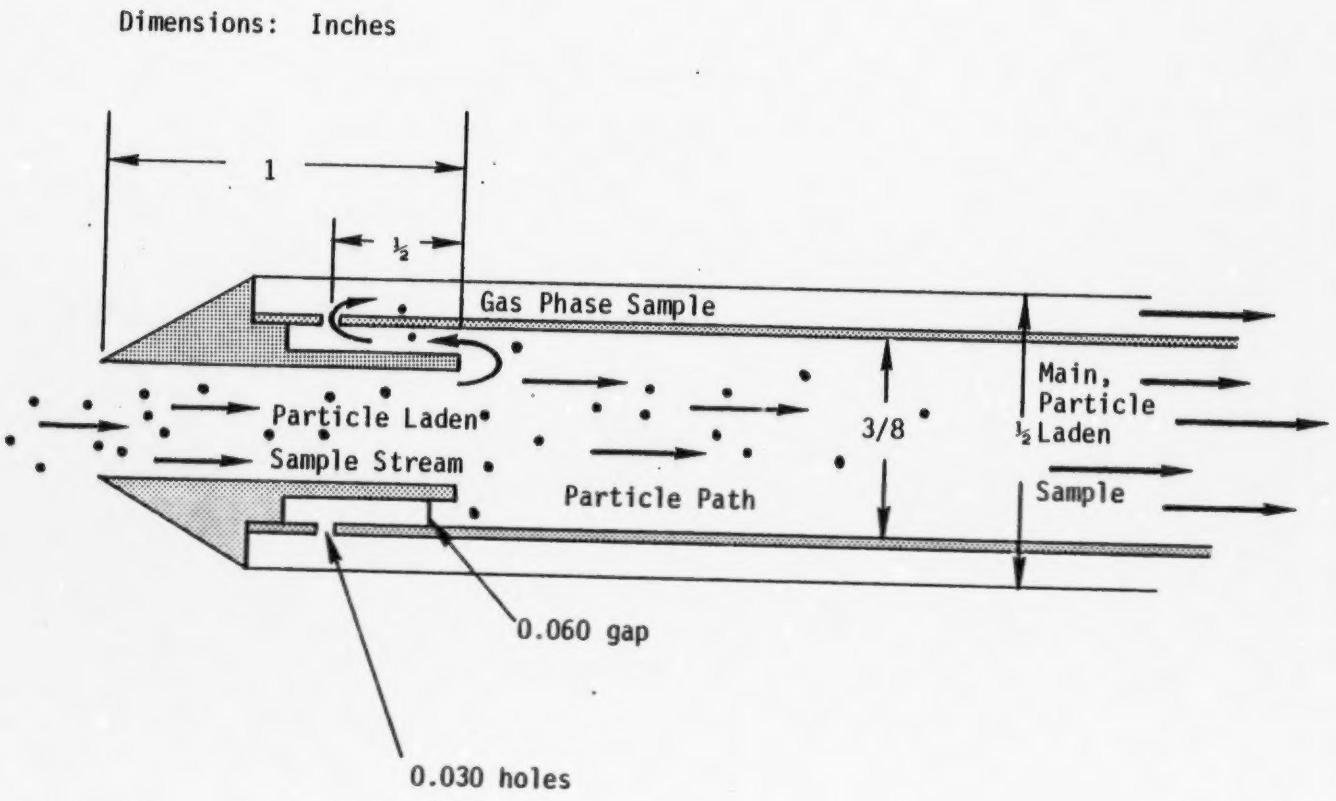

Dimensions: Inches
1
½
Gas Phase Sample
Main,
Particle
Laden
½
3/8
Particle Laden
Sample Stream
Particle Path
Sample
0.060 gap
0.030 holes

Figure A-1. Phase discrimination probe.

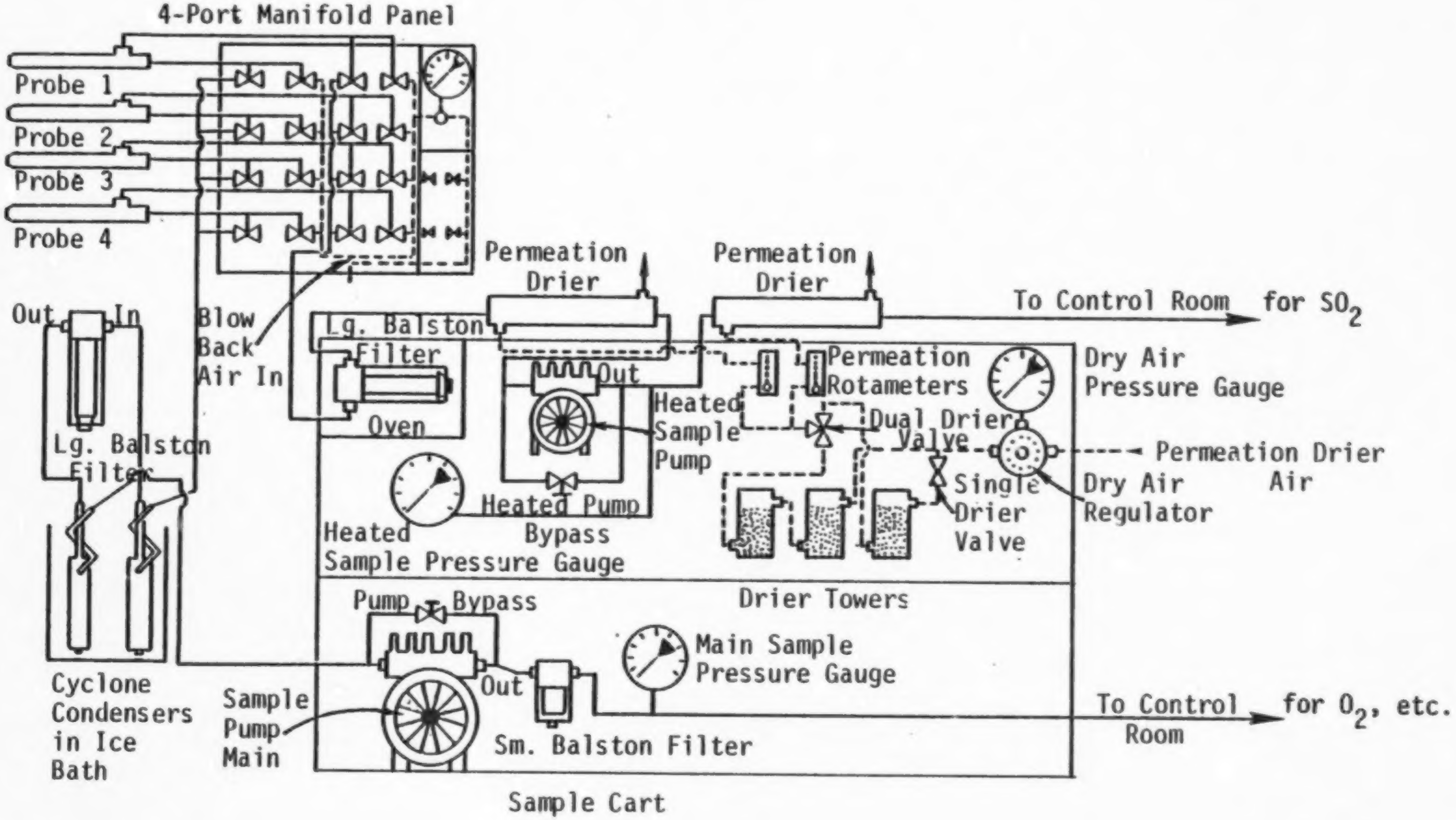

4-Port Manifold Panel
Probe 1
Probe 2
Probe 3
Probe 4
Out
In
Blow Back Air In
Lg. Balston Filter
Cyclone Condensers in Ice Bath
Permeation Drier
Permeation Drier
To Control Room for SO2
Lg. Balston Filter
Oven
Out
Heated Sample Pump
Permeation Rotameters
Dry Air Pressure Gauge
Dual Drier Valve
Permeation Drier Air
Dry Air Regulator
Single Drier Valve
Heated Pump Bypass
Heated Sample Pressure Gauge
Drier Towers
Pump Bypass
Main Sample Pressure Gauge
Sample Pump Main
Out
Sm. Balston Filter
To Control Room for O2, etc.
Sample Cart

Figure A-2. Sampling conditioning systems for O_2, CO, CO_2 and NO_x, and for SO_2

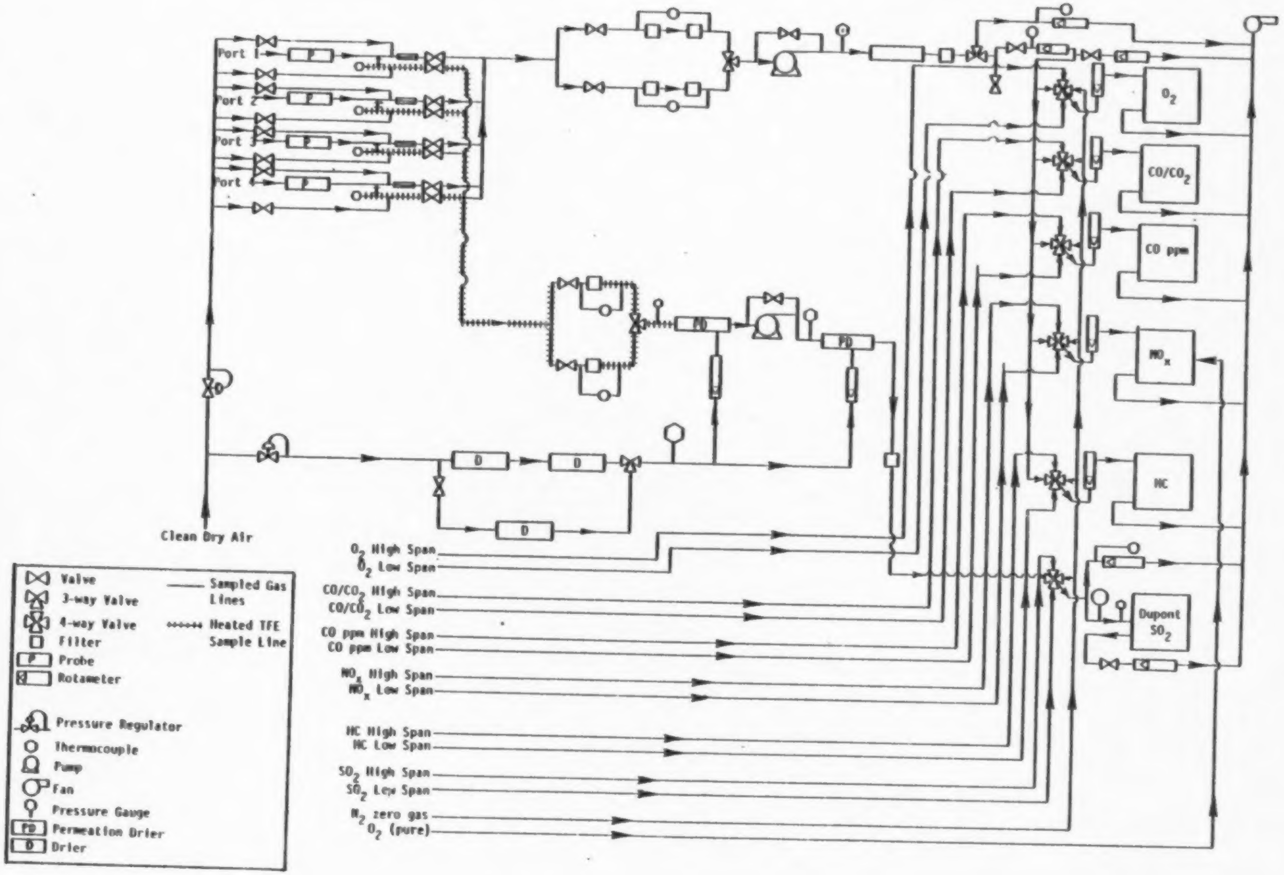

Port 1
Port 2
Port 3
Port 4
P
PD
D
O_2
CO/CO_2
CO ppm
NO_x
HC
Dupont SO_2
Clean Dry Air
O_2 High Span
O_2 Low Span
CO/CO_2 High Span
CO/CO_2 Low Span
CO ppm High Span
CO ppm Low Span
NO_x High Span
NO_x Low Span
HC High Span
HC Low Span
SO_2 High Span
SO_2 Low Span
N_2 zero gas
O_2 (pure)
Valve
3-way Valve
4-way Valve
Filter
Probe
Rotameter
Sampled Gas Lines
Heated TFE Sample Line
Pressure Regulator
Thermocouple
Pump
Fan
Pressure Gauge
Permeation Drier
Drier

Figure A-3. BSF - four probe sample and analytical system.

measured using a non-dispersive ultraviolet instrument manufactured by DuPont. The NDUV system was selected for simplicity, lack of interferences or quenching (a problem with pulsed-fluorescent SO_2 instruments) and linearity. The permeation drier was tested to assure that it did not pass SO_2, CO, CO_2, NO or O_2 across the semi-permeable membrane. The water removal efficiency of the drier was also demonstrated. Figure A-4 compares SO_2 concentrations without water vapor and after water vapor had been added to the gas and then removed in the permeation drier.

The sulfur measurement system was tested to insure that observed SO_2 reductions with sorbent injection were due to reactions occurring in the furnace rather than to reactions in the probe/sample system. The system was tested under conditions where the sulfur capture was high (in other words, where the sorbent particles were very reactive). The sample system was tested by injecting SO_2 just before the sample probe. If the reaction occurs in the furnace SO_2 injected immediately before the probe will not react with sorbent and a pulse of sorbent will not change the measured SO_2 concentration. Because the Boiler Simulator Furnace consistently exhibited a "profile" of SO_2 capture - capture at the exit of the radiant furnace was less than total capture at the exit of the post flame section which, in turn, was less than capture at the exit of the convective sections - the measurements test was performed at all three sample locations. SO_2 was injected shortly ahead of each probe and measured at the probe (and at each downstream probe) while the sorbent was pulsed on and off. Figure A-5 shows the SO_2 injection and sample locations.

Figure A-6 is a trace of the actual SO_2 instrument response to a pulse of sorbent (added with the propane) when the SO_2 was injected just before probe 3 (Location A) and measured at probe 3. It is clear that no sulfur capture is occurring in the sample system under these conditions. Figure A-7 shows the response at probe 2 (A-7a) and at probe 3 (A-7b) to a pulse of sorbent when the SO_2 was injected before probe 2 (Location B). The change in SO_2 measured at Port 2 (immediately after the SO_2 injection) was small (Figure A-7a). The measured sulfur capture at Port 3 (where the sorbent and SO_2 had significant furnace reaction time available) was considerably higher (see Figure A-7b). Figure A-8 shows the effect of a pulse of sorbent on the SO_2 measured at each of the three probes when the SO_2 was injected before Port 1 (Injection Loca-

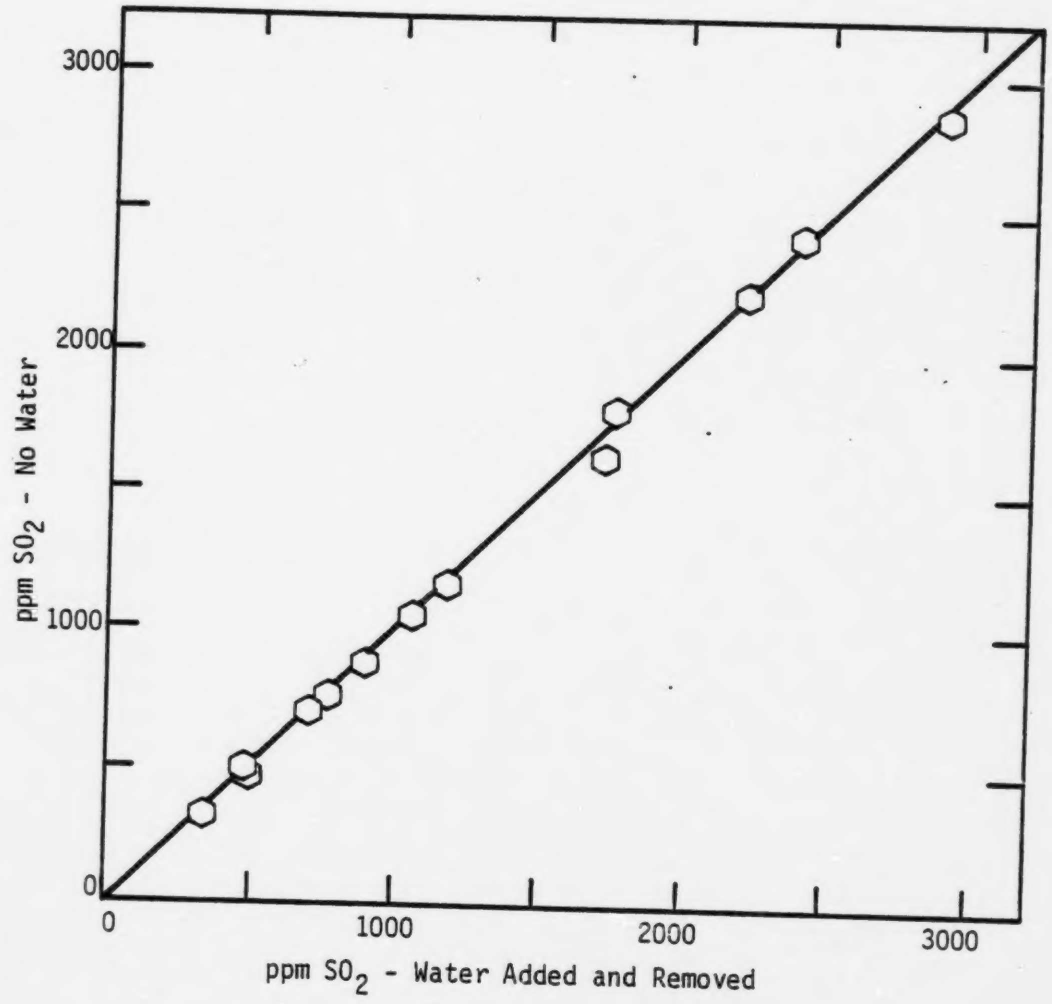


Figure A-4. Verification of permeation tube drier.

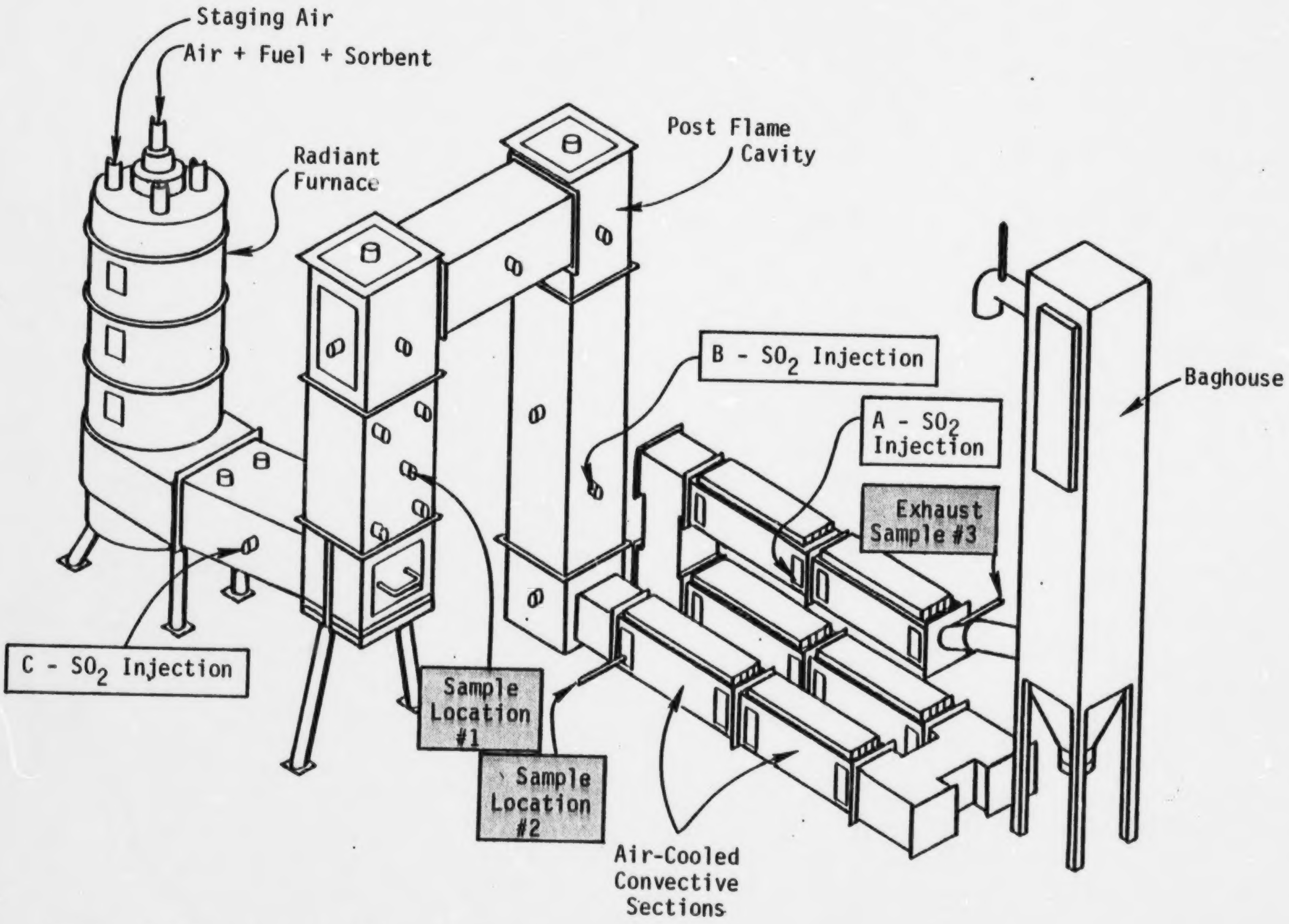

Staging Air
Air + Fuel + Sorbent
Radiant Furnace
Post Flame Cavity
B - SO_2 Injection
A - SO_2 Injection
Exhaust Sample #3
Baghouse
C - SO_2 Injection
Sample Location #1
Sample Location #2
Air-Cooled Convective Sections

Figure A-5. Schematic of Boiler Simulator Furnace; SO_2 injection and sampling locations.

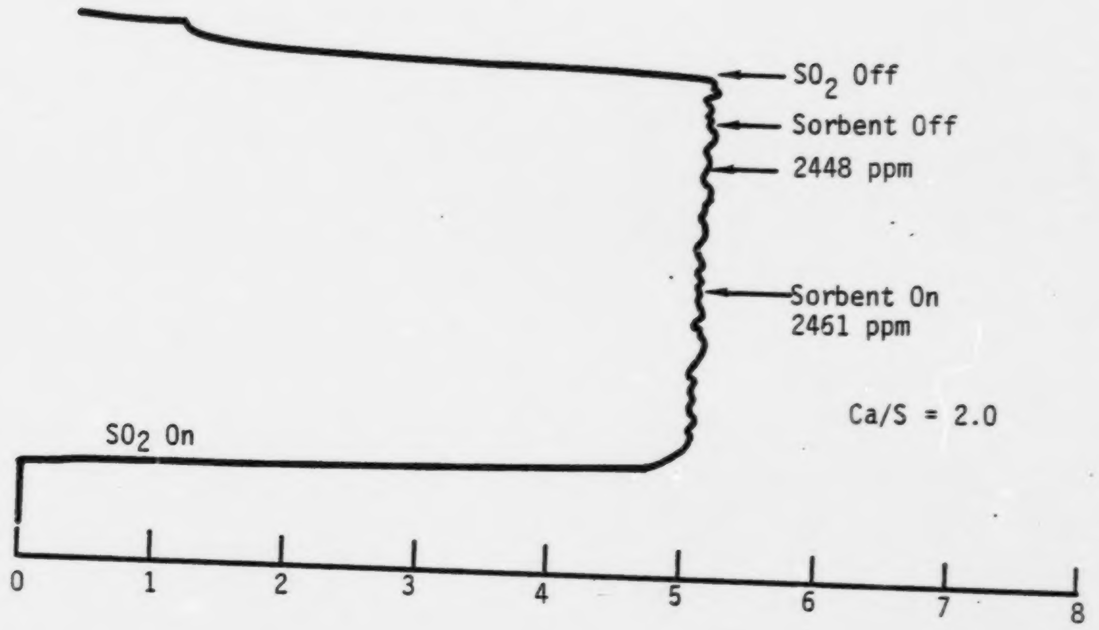
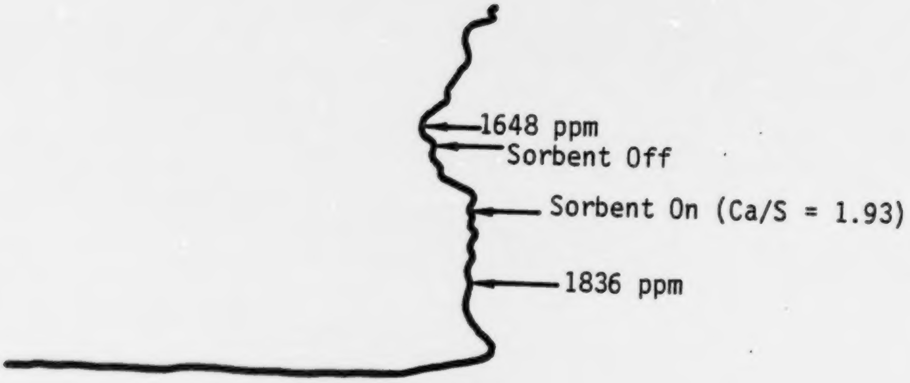
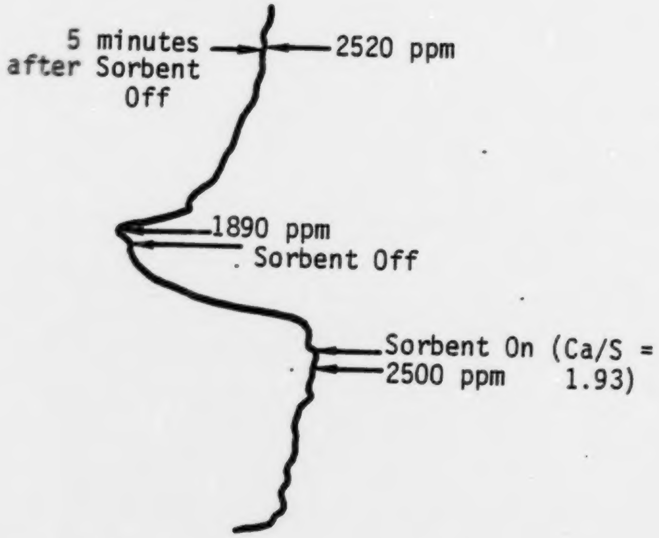


Figure A-6. Measurement system test; SO_2 injection at convective section (Location A), measured at probe 3.

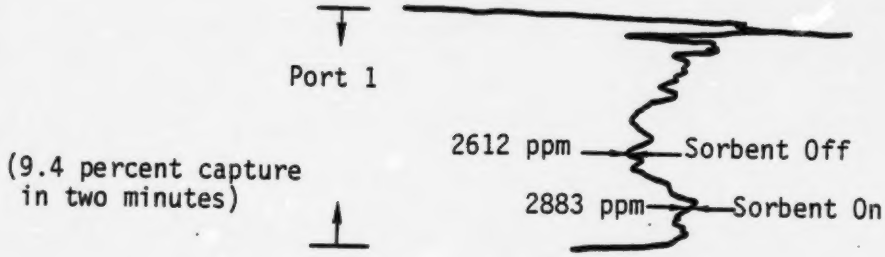


a. SO_2 Injected at B, Measured at Port 2

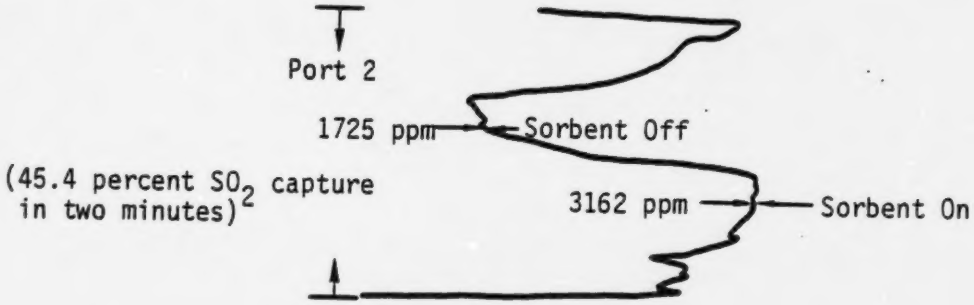


b. SO_2 Injected at B, Measured at Port 3

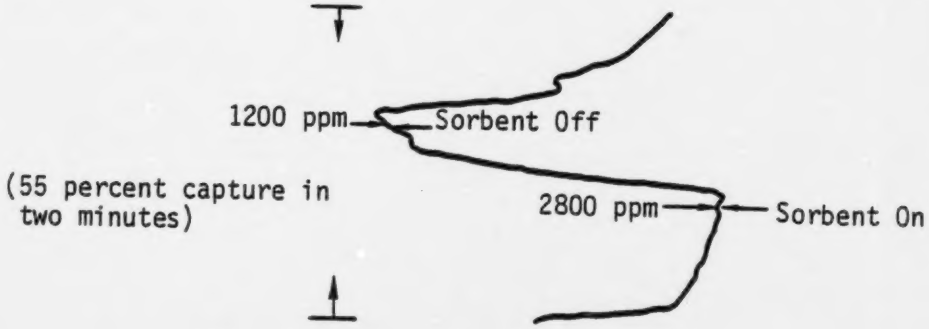
Figure A-7. Measurements system test; SO_2 injection at post flame cavity (Location B), measured at Port 2 and at Port 3



a. SO_2 Injected at C, Measured at Port 1



b. SO_2 Injected at C, Measured at Port 2



c. SO_2 Injected at C, Measured at Port 3

Figure A-8. Measurement system test; SO_2 injected at entrance of postflame cavity.

tion C). Figure A-8a shows the response at Port 1 to a pulse of sorbent. Figures A-8b and A-8c show the response at Ports 2 and 3. The SO_2 injection location and sorbent injection location were not changed. Again, little change in SO_2 due to sorbent injection was observed with the sample probe located immediately behind the SO_2 injection location. Significant levels of sulfur capture occurred in the post flame cavity (sampling at Port 2) and in the convective passages (sampling at Port 3). These measurement tests indicate that the observed sulfur capture is indeed occurring in the furnace and not in the sample system.

After the gas samples were extracted from the furnace and conditioned they were delivered to a set of continuous analytical instruments (Table A-1). The instruments used were selected for reliability, ease of operation and cost. There is considerable experience at EER with standard CO, CO_2, O_2, and NO_x instrumentation. This experience was drawn on in selection and setup of the particular instrumentation with little effort spent on new developments. Continouous measurement of SO_2 was made with a non-dispersive ultraviolet instrument manufactured by DuPont. SO_2 is measured by the difference in absorption of ultraviolet radiation by the sample gas at two wavelengths--a reference wavelength and at 320 nm which is absorbed specifically by SO_2. The NDUV instrument was chosen in preference to a pulsed fluorescent instrument because of the linearity and stability of the DuPont and because there is not interference from H_2O, CO_2, or O_2 as there is (due to quenching of the fluorescence) in the pulsed fluorescent instrument. The DuPont instrument and sampling system were compared with EPA Method 7 SO_2 measurements under both cold (SO_2 + air) and flame conditions. The agreement was good and was not affected by water vapor content or SO_2 concentration.

The DuPont instrument is suitable for measurement of SO_2 in combustion stack gases but aromatic and unsaturated hydrocarbons absorb U.V. light in the same wavelengths as SO_2; therefore, the DuPont cannot be used to directly measure SO_2 in fuel rich combustion gases. Sulfur specie measurements in rich gases were made in two ways. On a continuous basis SO_2 and H_2S were measured using a catalytic converter system to oxidize the H_2S to SO_2. The continuous H_2S measurement system consisted of a dilution system to add O_2 to the sample, a heated catalytic converter and a SO_2 selective scrubber (see Figure A-10). H_2S was measured by diluting the sample with O_2, oxidizing the H_2S to SO_2 in

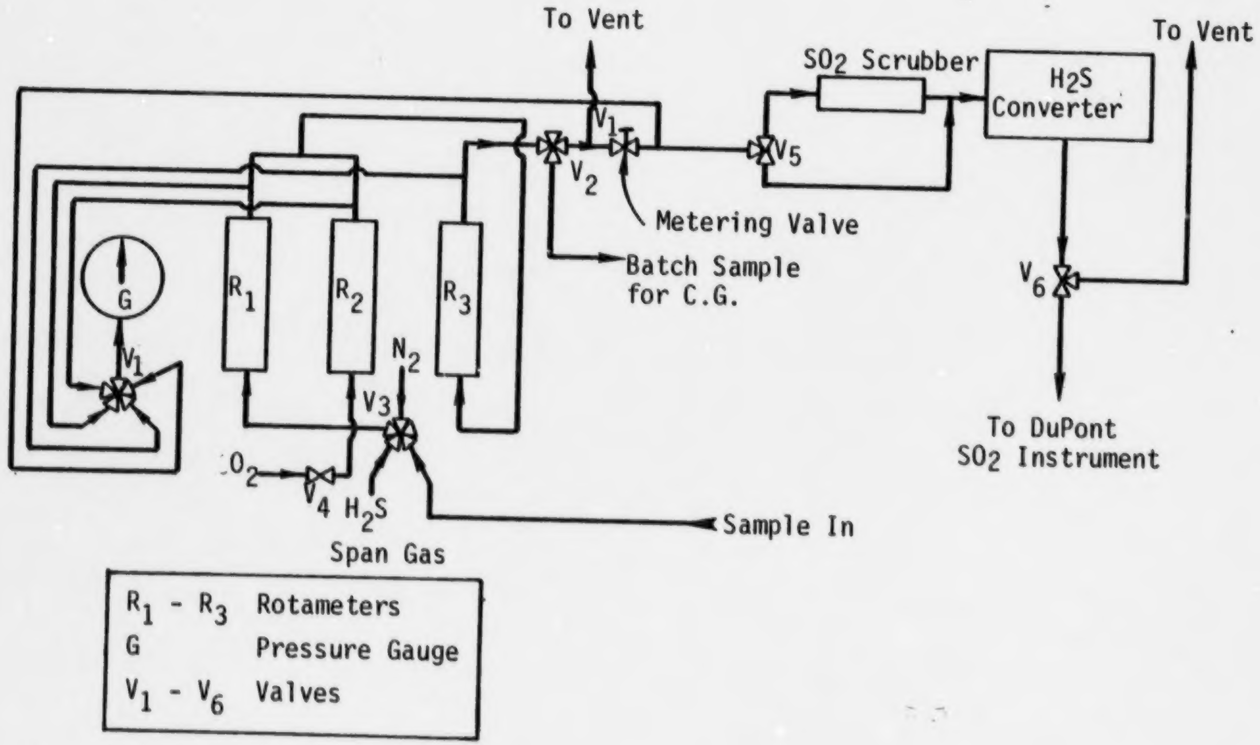

To Vent
To Vent
SO_2 Scrubber
H_2S Converter
V_1
V_2
V_5
V_6
Metering Valve
Batch Sample for C.G.
To DuPont SO_2 Instrument
G
V_1
R_1
R_2
R_3
N_2
V_3
O_2
V_4
H_2S Span Gas
Sample In
R_1 - R_3 Rotameters
G Pressure Gauge
V_1 - V_6 Valves

Figure A-10. Sample conditioning system for H_2S

the converter and measuring the resulting SO_2 concentration with the DuPont. SO_2 was measured as the difference between total SO_2 (all the sample gas through the converter) and H_2S (the sample was routed through the SO_2 scrubber before oxidizing). Figure A-11 shows the agreement between measured SO_2 and expected (based on dilution SO_2 concentrations for various SO_2 and H_2S span gas/air mixtures).

A gas chromatograph equipped with a flame photometric detector was used to measure sulfur species (including CS_2 COS, thiophene and other sulfur-containing hydrocarbons in addition to H_2S and SO_2) in the fuel rich gas samples. The GC system is by necessity a batch system; samples were taken in glas flasks and stored for subsequent analysis. The GC system used for these studies consists of a Perkin Elmer model Sigma 10 temperature programmable gas chromatograph equipped with a flame photometric detector and a gas sampling valve. An acetone-washed, porapac-QS column 1/8 in x 2 ft was used to separate the sulfur gases. The oven was temperature programmed to optimize sample separation and total analysis time. The flame photometric detector (FPD) is sulfur specific. It operates by measuring light emitted by sulfur atoms as sulfur compounds are burned in a hydrogen/air flame.

The FPD response is approximately linear with the square of the mass flow rate of sulfur through the detector but the response varies significantly among sulfur-containing compounds. Because the detector response is compound dependent, calibration curves for each sulfur compound of interest had to be constructed. Furthermore, the gas chromatograph/column/detector system was observed to absorb some sulfur at the beginning of a test or calibration series if the system had not been exposed to sulfur-containing gases for several hours. This difficulty was overcome by injecting a standard gas mixture onto the column at least six times before sample gases were analyzed. The data shown in Figure A-12 indicate that six injections of the gas mixture (H_2S was absorbed more than the other species) are sufficient to saturate the column before a test run.

The gas samples, either calibration gases or test samples, were injected under vacuum onto the GC column with a constant volume gas sample loop and sampling valve. The sample loop was evacuated, filled with sample, the sample pressure noted and then the sample was injected onto the column (see Figure

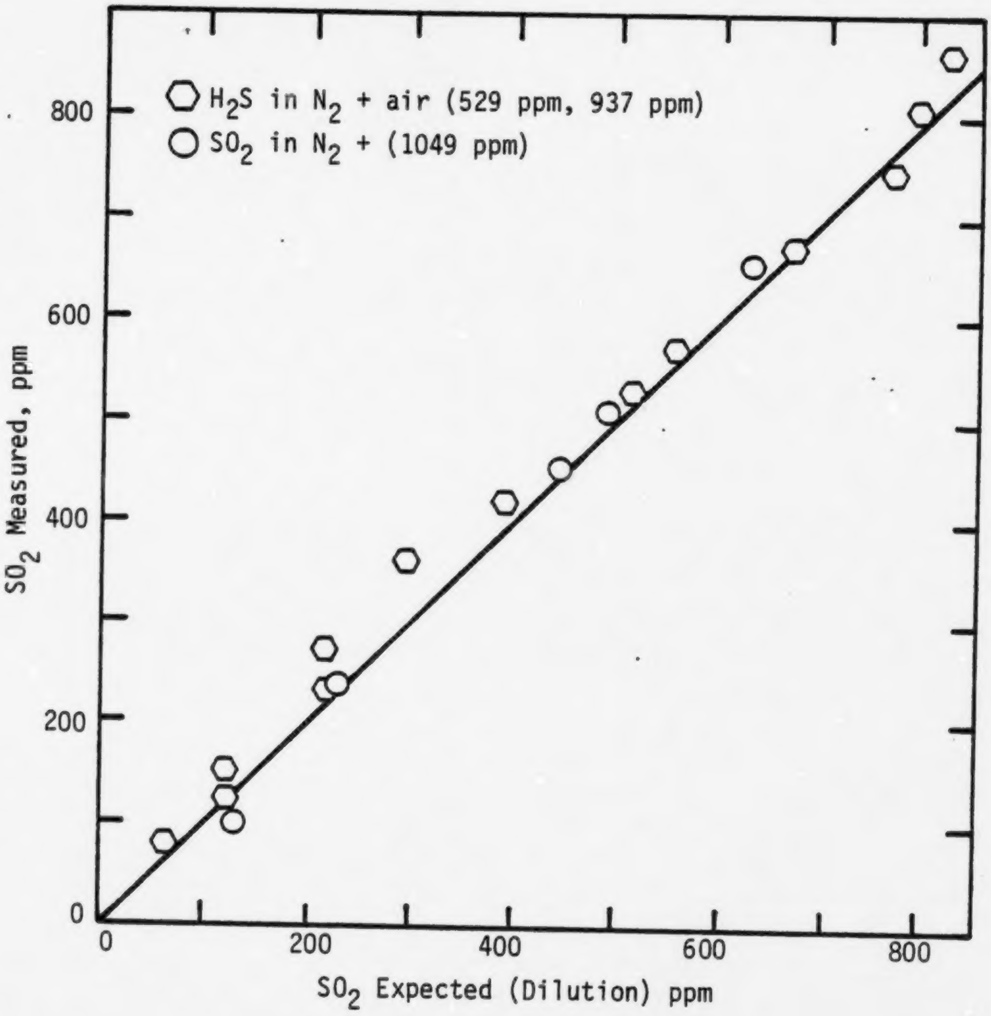


Figure A-11. H_2S measurement verification.

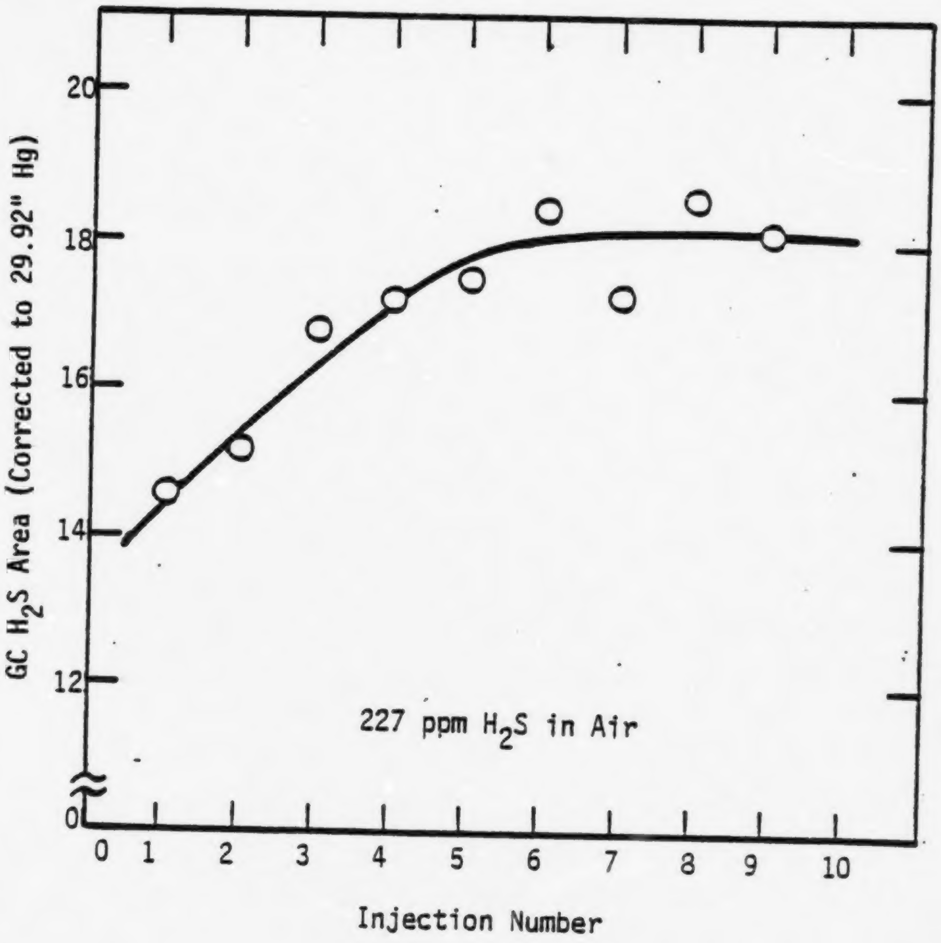


Figure A-12. Retention of H_2S in GC System at Start-Up.

A-13). The calibration standards were injected in the same manner as the test samples. The calibration curves were standardized to 29.92" Hg and the sample responses were corrected to the same basis. The system was tested with a mixture of sulfur species in air and with samples from the BSF. Figure A-14 shows an example ofthe separation achieved with an actual sample. The various sulfur species retention times and chromatographic conditions are also indicated.

The two H_2S/SO_2 measurements systems (the GC and O_2 dilution and convertor/scrubber system) were used to analyze several samples from the furnace and gave good agreement in most cases. A problem arose with the continuous H_2S system because a significant amount of the sulfur in the sample was COS which is not quantitatively oxidized by the converter and therefore not accurately measured with the continuous system. The converter could not be used to give data for a sulfur balance when significant amounts of sulfur were present as COS.

A.2 Solid Samples

Solid samples were taken from the furnace in two ways: isokinetically with a filter-tipped, water cooled probe, and non-isokinetically with a water cooled "grab sample" probe and glass cyclone. The isokinetic sampling system consisted of a probe made at the International Flame Research Foundation, shown schematically in Figure A-15, and a heated teflon sample line followed by a pump, dry gas meter, pressure gauge, and rotameter for the measurement of the sample flowrate. The grab sample was taken from the furnace with a standard, stainless-steel, water-cooled probe and the solids removed from the sample with a glass cyclone.

The solids characteristics which were measured are listed in Table A-1. The measurements are briefly described, with emphasis given to those measurements of special importance to the bench scale sorbent injection studies. Carbon, hydrogen, nitrogen, ash and oxygen contents of solid samples were measured using a Perkin-Elmer Model 240B elemental analyzer. Sulfur was measured using an instrument manufactured by LECO. The LECO was designed to measure the sulfur content of combustible solids and had to be tested with sorbent and ash samples. The instrument burns the sample at high temperature (>2400°F) in an oxygen-enriched atmosphere) and measures, by integrating over the combustion time light absorbed at a specific wavelength in the infrared region,

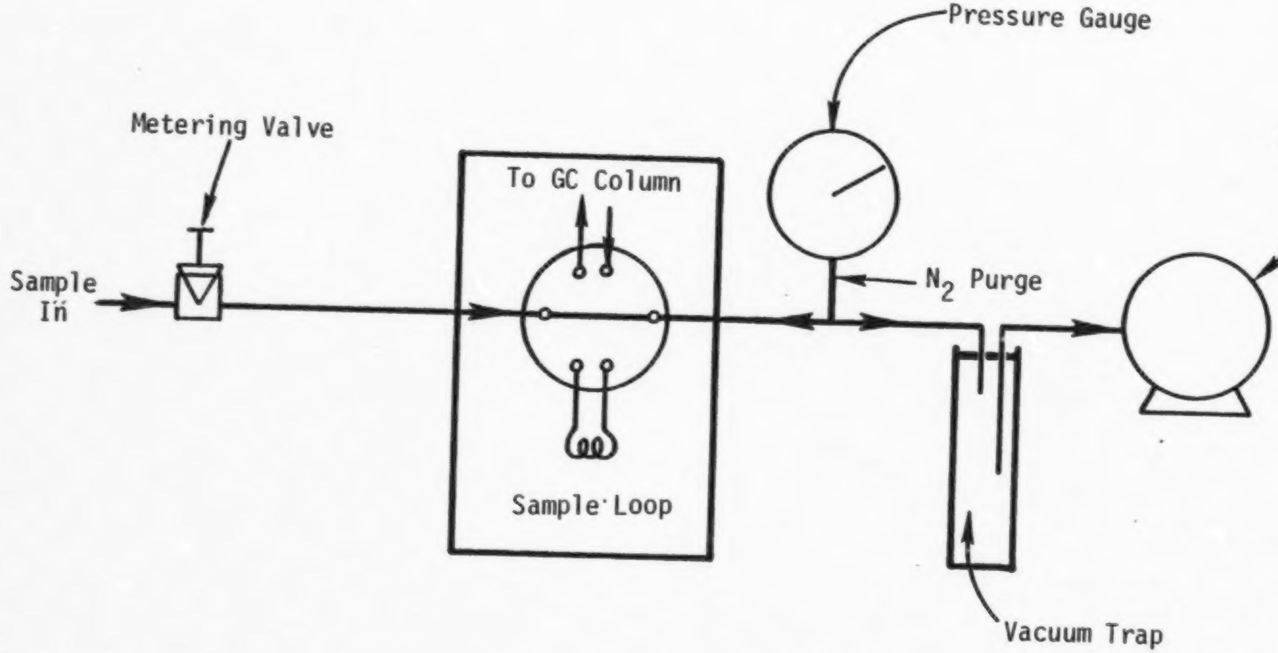
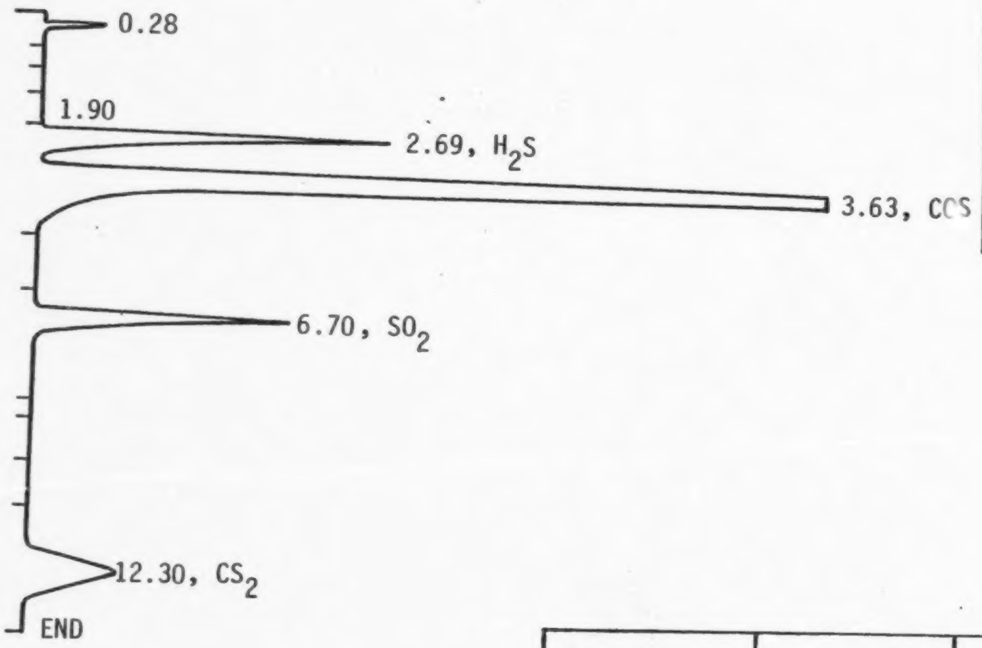

Pressure Gauge
Metering Valve
Pump
To GC Column
Sample In
N_2 Purge
Sample Loop
Vacuum Trap

Figure A-13. Flow diagram of GC sampling system.



Chromatography Data
Porapac QS, Acetone washed, 2' x 1/8" Teflon column; Temperature programmed He Carrier Gas at 30 cc/min

Retention Time	Species	Reduced Area (29.92" Hg)	ppm
2.69	H_2S	0.896	16
3.63	COS	7.099	67
6.70	SO_2	0.939	18
12.30	CS_2	0.627	<1

Figure A-14. Typical gas chromatogram of first stage sample (fuel rich).

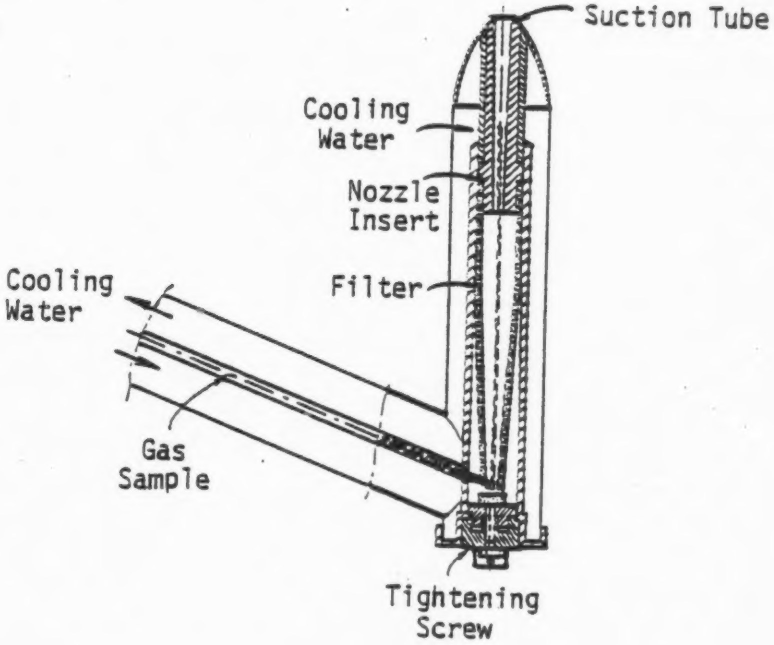

Suction Tube
Cooling Water
Nozzle Insert
Cooling Water
Filter
Gas Sample
Tightening Screw

Figure A-15. International Flame Research Foundation Solid Sampling Probe.

the SO_2 evolved. The instrument is equipped with an analytical balance and a microprocessor system which are used to convert the measured SO_2 content of the gases to equivalent weight percent of sulfur in the sample. Noncombustible solids, including calcium salts and coal ashes, require the use of a combustion accelerator to insure that all of the sulfur is evolved from the sample. Several combustion accelerators were tested, including V_2O_5, Al_2O_3, and MgO; V_2O_5 was the best for use with sorbent and ash samples.

Several standards were prepared to determine the accuracy of the sulfur measurement methods developed. Calcium sulfate ($CaSO_4$), pure reagent grade, was mixed in known proportions (by mass) with pure, dry, unreacted calcium carbonate. The sulfur content of these standards was measured and compared to the expected sulfur content. These results are shown in Figure A-16. There was good agreement between the measured and expected values of sulfur. Each point plotted is an average of at least six measurements. Blanks, containing pure $CaCO_3$ or $Ca(OH)_2$, were run before each measurement.

The surface area of the solid sorbent powders and of ash/sorbent samples from the furnace was determined by gas absorption using an instrument manufactured by Quantachrome, Inc. This instrument is based on the BET method, where surface area is related to the monolayer capacity of an adsorbent. The BET surface reas of porous and nonporous samples are conventionally determined from N_2 adsorption isotherms measured at 77 K. Single or multipoint BET surface area measurements, with either N_2 or CO_2 as the adsorbate, can be made. Sorbent or ash/sorbent sample surface areas were measured using a two-point BET surface area with N_2 as the adsorbate gas. The two-point method was sufficient because the solids behave in a very nearly ideal manner. N_2 was used as the adsorbate because it is easier to use than CO_2 and to eliminate any possibility of a back reaction between CaO in the ash samples and CO_2 to form $CaCO_3$.

The ability to assess sorbent reactivity is of key importance. Two standard methods of characterizing sorbent reactivity were developed. One method of assessing the degree of deadburning of a calcine is to determine the rate of disassociation of the calcine in water. A calcine which has been deadburned will dissociate more slowly than one with an open porous structure, a "softburned" stone. A deadburned stone will be less reactive than a stone

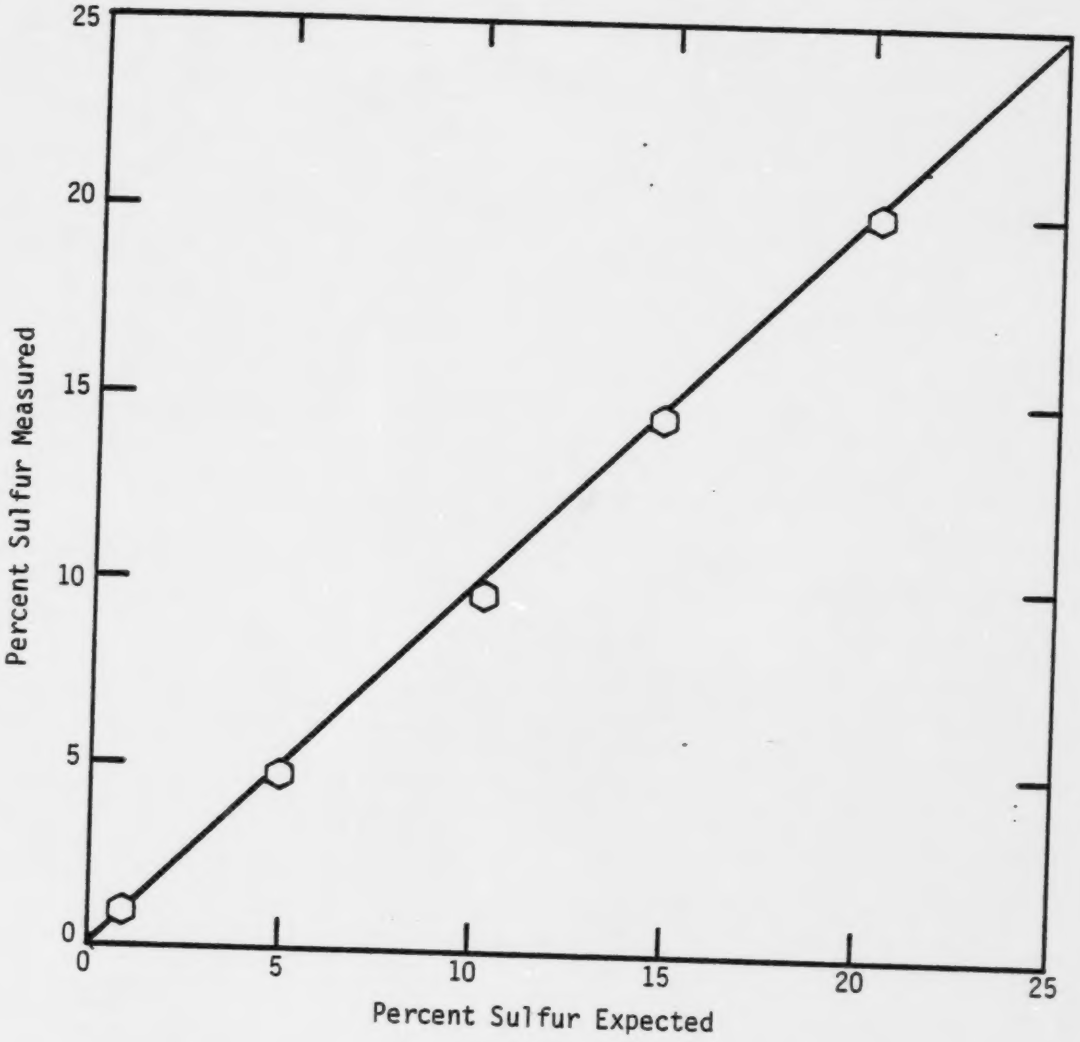


Figure A-16. Calibration curve for known sulfur standards on LECO analyzer.

which is softburned because when a particle deadburns, the pore structure begins to collapse and less surface area is available for reaction. The rate of dissociation of a sorbent in water is conveniently measured by stirring a known amount of stone in water and titrating the solution with acid to a constant pH (generally to the neutral point, 7.0) at timed intervals. The time it takes a stone to dissociate completely (or to add the acid equivalent to the stone) is a simple measure of the sorbent's reactivity. This dissociation test is only useful for unsulfated stones and cannot be used on sorbent/fly ash mixtures because the presence of acidic or basic compounds will interfere with titration of the sorbent to the neutral point. The dissociation characteristics of various calcines are different; however, the dissociation rate of a given stone is affected by deadburning in a predictable manner.

A second test for the degree of overburn or deadburning of a sorbent is the hydration weight gain of the solid. The solid sample is dried at a temperature sufficient to remove moisture associated with the solids; water is added, allowed to react with the solids, and evaporated. The weight gain associated with this water uptake can be related to the degree of overburn of the sorbent. The hydration weight gain test may be used on sulfated samples and on sorbent/ash mixtures. However, the interpretation of the weight gain results requires the characterization of the pure sorbent in terms of deadburning versus dissociation rate and deadburning versus hydration weight gain. A characteristics weight gain for a deadburned or softburned sorbent is established and compared to weight gains measured for some of the standard calcines described earlier.

B.3 Temperature Measurement

Furnace wall temperatures were measured using thermocouples embedded in the refractory walls. Temperatures in the radiant and post flame section were measured using platinum/platinum-rhodium (Type S) thermocouples. Temperatures in the convective sections were measured using chromel/alumel (Type K) thermocouples.

Gas temperatures were measured using a suction pyrometer. The pyrometer and thermocouple were standard for both gas and coal flames (see Figure A-17). The ceramic shield was chosen to match the fuel. An open ended shield (A-17a) was used in optically-dense ash laden coal flames in order to limit plugging

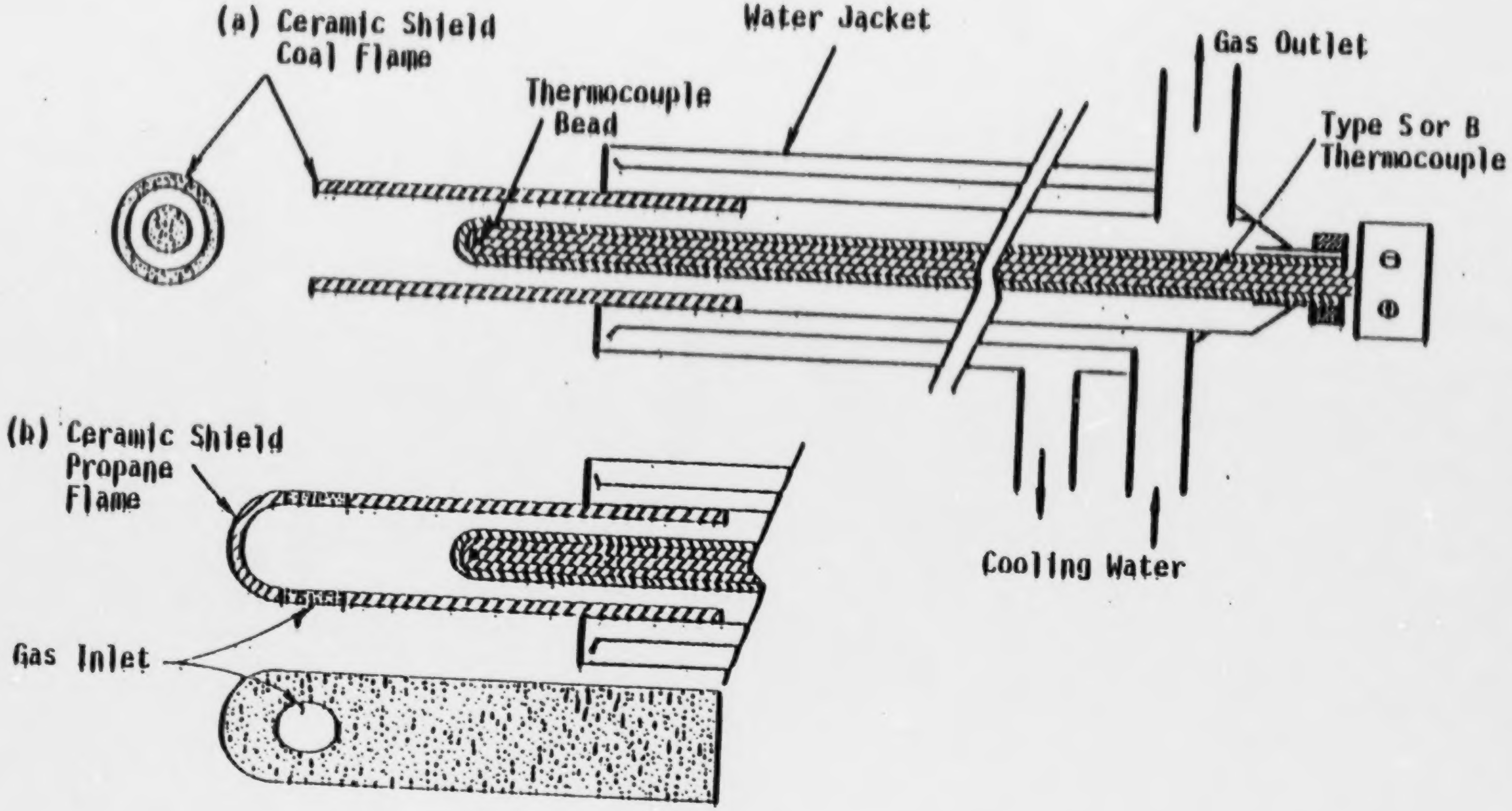

(a) Ceramic Shield
Coal Flame
Water Jacket
Gas Outlet
Thermocouple
Bead
Type S or B
Thermocouple
Cooling Water
(b) Ceramic Shield
Propane
Flame
Gas Inlet

Figure A-17. Suction Pyrometer Schematic.

of the probe tip (and because radiant losses through the open end of the shield are small in the ash laden gases). A closed end ceramic shield with holes parallel to the gas flow (A-17b) was used for gas temperature measurements in the propane flame.

APPENDIX B

FACILITIES

APPENDIX B

EXPERIMENTAL FACILITIES

The experiments discussed in this report were performed in four facilities. The preliminary program definition experiments that were performed during the design and construction of the Boiler Simulator Furnace (BSF) used three already existing small scale (70,000 to 100,000 Btu/hr) furnaces. The major portion of the experimental work was performed using the Boiler Simulator Furnace. The three small furnaces are briefly described and the Boiler Simulator Furnace is discussed in more detail.

B.1 Small Tunnel Furnaces

Three downfired, refractory-tunnel furnaces were used for the program definition experiments. Two of these furnaces were fired on coal. One of the coal fired furnaces was equipped with convective cooling sections and had been used for ash characterization studies. The other coal fired furnace had been used for fuel nitrogen studies and was equipped with an argon/carbon dioxide/oxygen oxidant system for the fuel studies. Both furnaces were fired with coal/air using premixed burners. Figures B-1 and B-2 show schematics of the two coal fired furnaces.

The third tunnel furnace was very similar to the coal-fired, fuels-study furnace in construction but was fired with propane using a diffusion burner. This furnace was equipped with a separate sorbent feeder and a gas metering system for the addition of sulfur species to the fuel or combustion air. The overall furnace, additive and sampling system is shown schematically in Figure B-3. Schematics of individual components (burner, gas additive/metering system, and sorbent feeding system) are shown in Figures B-4 through B-6. All of the gas fired, program definition experiments were done using these systems.

B.2 Boiler Simulator Furnace

The major portion of the experiments discussed used the Boiler Simulator Furnace (BSF) and its auxiliary systems. The design and construction of the BSF was a portion of the program effort. The furnace and operating experience with the furnace system are described in this section.

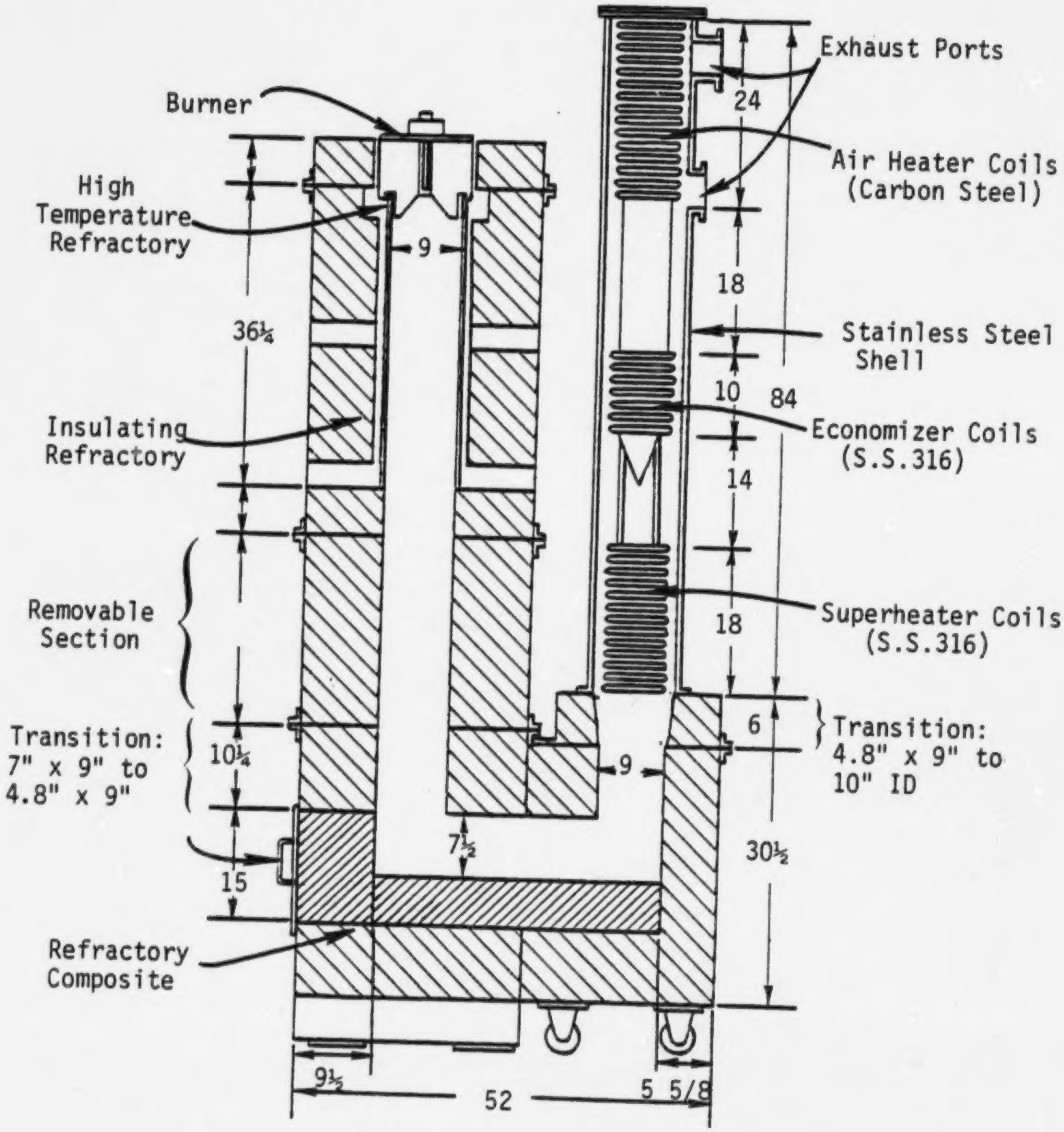

Burner
High Temperature Refractory
9
36¼
Insulating Refractory
Removable Section
Transition: 7" x 9" to 4.8" x 9"
10¼
15
7½
Refractory Composite
9½
52
5 5/8
Exhaust Ports
24
Air Heater Coils (Carbon Steel)
18
Stainless Steel Shell
10
84
Economizer Coils (S.S.316)
14
Superheater Coils (S.S.316)
18
6
Transition: 4.8" x 9" to 10" ID
9
30½

Figure B-1. Cross-section schematic of the combustor, convective furnace.

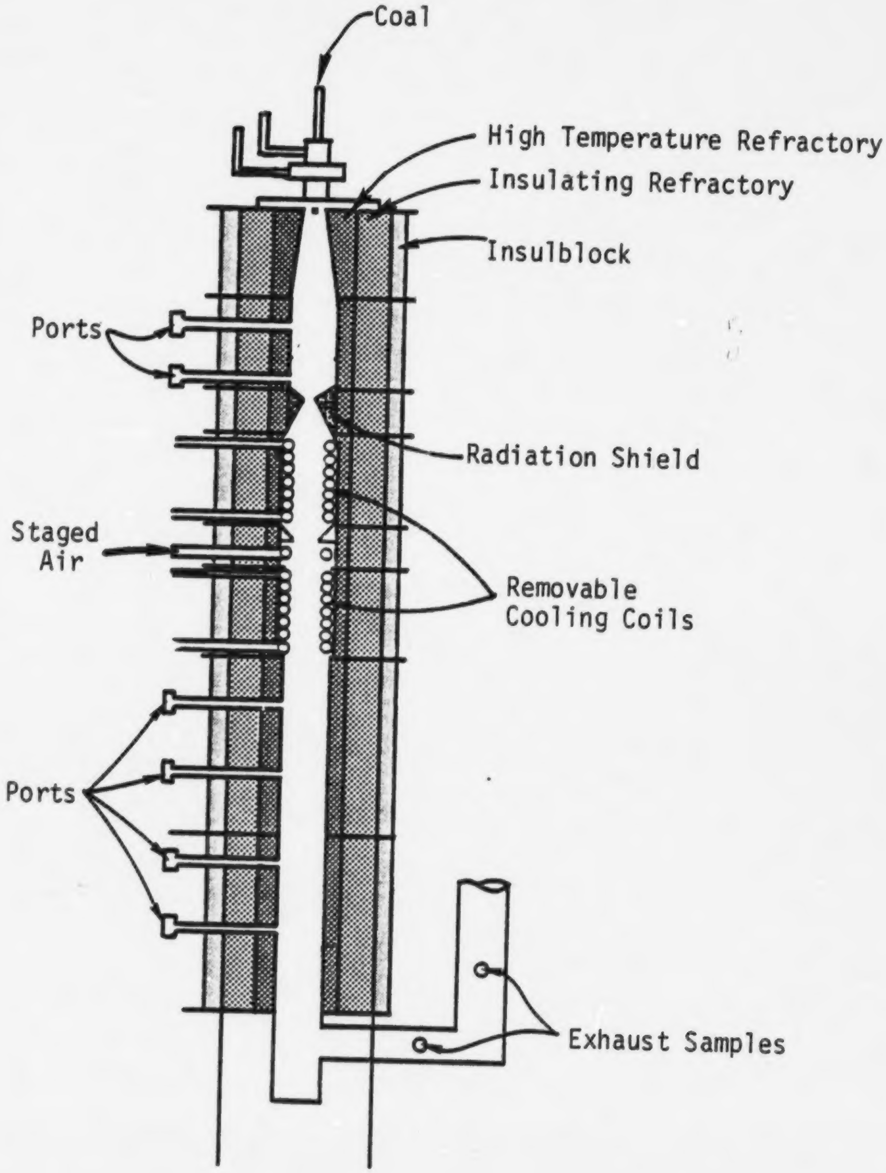

Coal
High Temperature Refractory
Insulating Refractory
Insulblock
Ports
Radiation Shield
Staged Air
Removable Cooling Coils
Ports
Exhaust Samples

Figure B-2. Bench scale reactor, fuels studies.

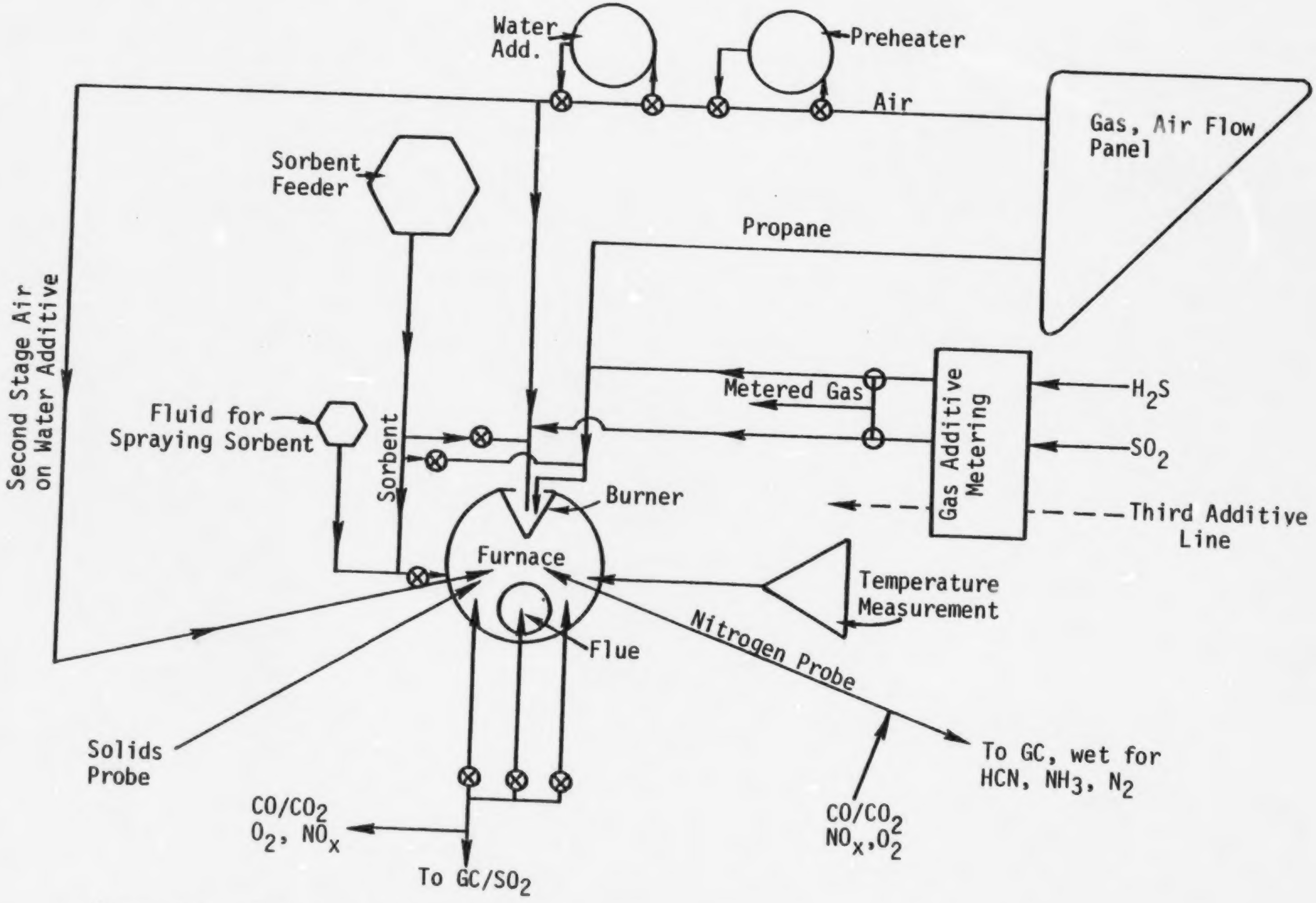

Water Add.
Preheater
Air
Gas, Air Flow Panel
Sorbent Feeder
Propane
Second Stage Air on Water Additive
Metered Gas
Gas Additive Metering
H_2S
SO_2
Fluid for Spraying Sorbent
Sorbent
Burner
Third Additive Line
Furnace
Temperature Measurement
Nitrogen Probe
Flue
Solids Probe
To GC, wet for HCN, NH_3, N_2
CO/CO_2 O_2, NO_x
To GC/SO_2
CO/CO_2 NO_x,O_2

Figure B-3. Schematic of experimental system for gas phase sulfur experiments, propane furnace.

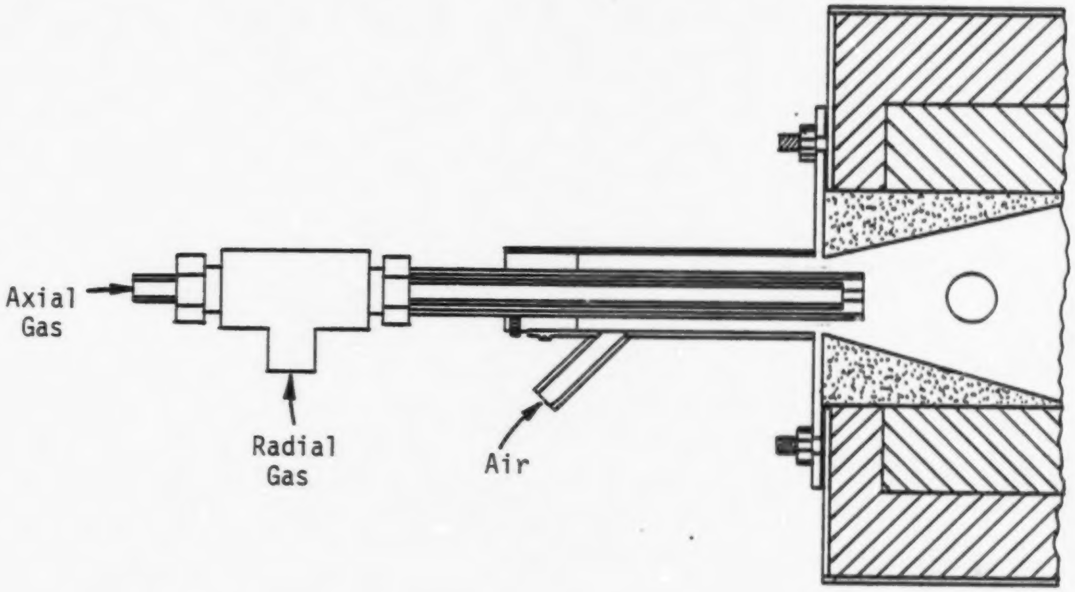

Axial Gas
Radial Gas
Air

Figure B-4. Burner schematic, propane furnace.

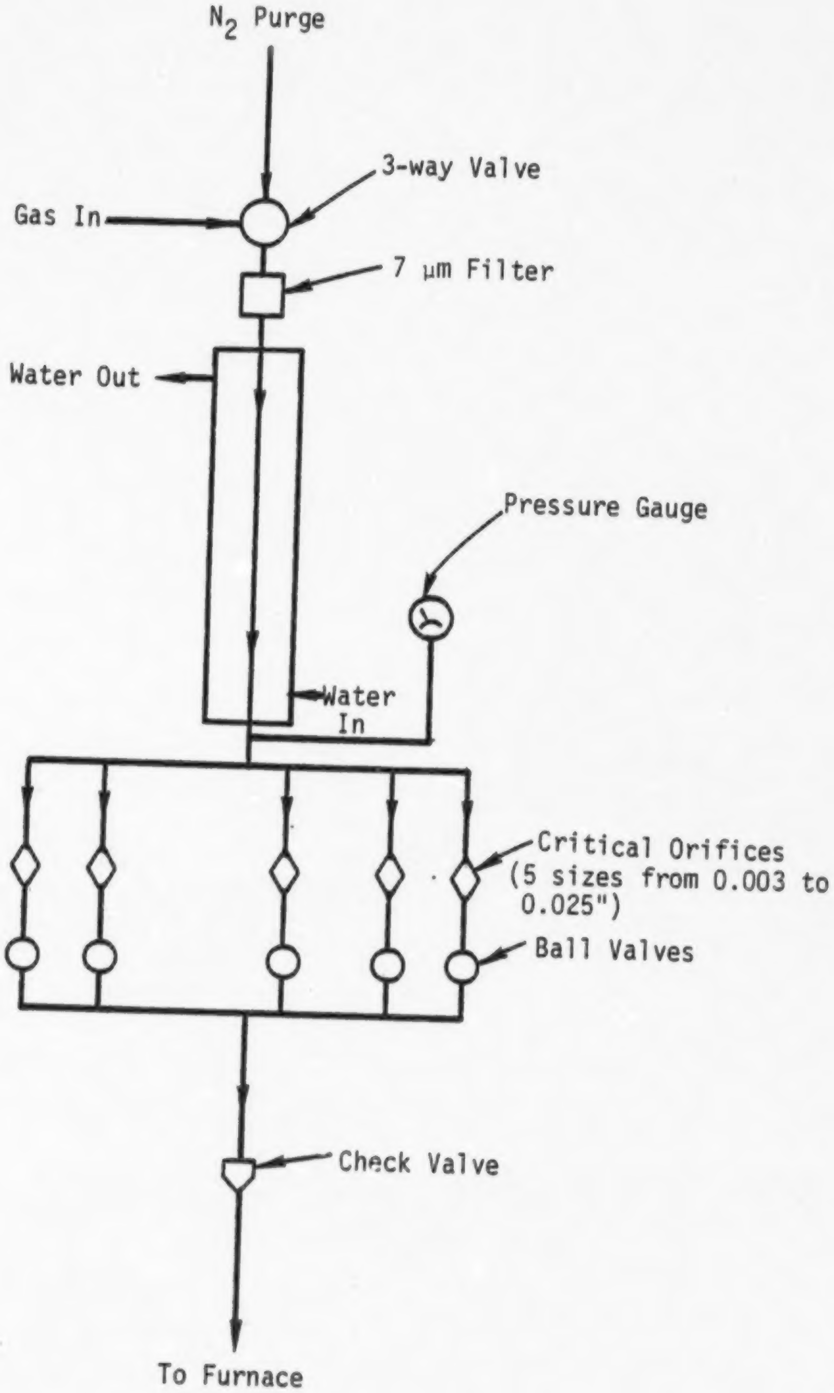

N$_2$ Purge
3-way Valve
Gas In
7 μm Filter
Water Out
Pressure Gauge
Water In
Critical Orifices (5 sizes from 0.003 to 0.025")
Ball Valves
Check Valve
To Furnace

Figure B-5. Gas additive system; all components are 316 stainless steel or Teflon.

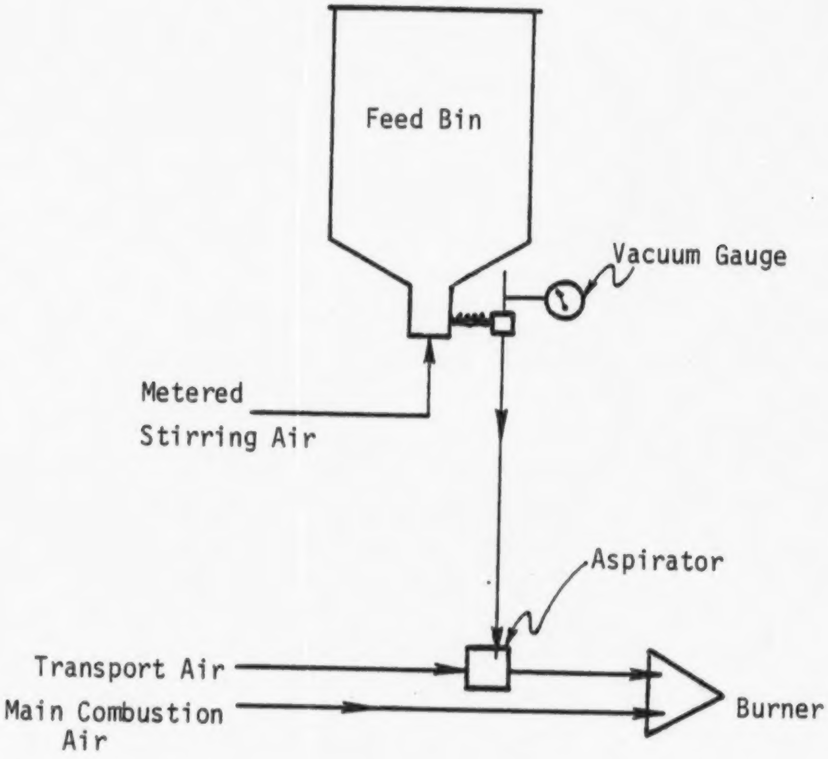

Feed Bin
Vacuum Gauge
Metered
Stirring Air
Aspirator
Transport Air
Main Combustion
Air
Burner

Figure B-6. Solids transport system, propane furnace.

The Boiler Simulator Furnace (BSF) was developed for studying sulfur pollutants from boilers as a part of Task 2 of EPA Contract No. 68-02-2667. The BSF experimental furnace system was designed to produce variable combustion conditions in order to simulate a wide variety of coal combustor firing schemes including:

- Wall firing
- Tangential firing
- Turbo
- Arch
- Tower
- Steamer
- Cyclone

There was no attempt to simulate directly the hardware of each of these types of firing systems; the BSF design tried to include conditions typical of the various systems. In particular, the unit was designed to simulate the time/temperature/stoichiometry history of an actual full scale, utility boiler. Detailed consideration of the flame zone, radiant zone, convective passages and the particle collection equipment were included in the design-criteria review. The furnace was designed to operate over a wider range of combustion conditions than are typical of current commercial practice.

The design criteria included the following:

- Independent control of wall temperature throughout the furnace and convective sections.
- Fuel consumption rate nominally 80 lbs/hr (1×10^6 Btu/hr, coal).
- Variable burner design.
- Variable preheat of all combustion air streams.
- Simulation of large particle-loss to furnace bottom.
- Ability to quickly and easily clean interior sections.
- Potential for near adiabatic operation by minimizing heat losses.

- Ease of access for sampling probes.

The experimental facility is suitable for the nitrogen and sulfur oxides studies currently in progress and is also suitable for investigations on particulate formation, slagging and fouling.

A functional schematic of the overall Boiler Simulator Furnace (BSF) is shown in Figure B-7. The relationship between the furnace elements and a typical utility boiler is indicated. The functional elements of the BSF system include:

- Fuel supply
- Sorbent supply
- Air supply
- Burner
- Furnace
- Clean-up
- Data acquisition

The key design considerations of each system are indicated in Figure B-8.

The fuel system has two subsystems: a coal supply system and a gas propane) supply system. The coal is batch pulverized, stored under nitrogen in bins and delivered to a twin-screw, loss-in-weight feeder for metering to the burner. The coal is transported from the feeder to the burner with metered primary air. A removable nozzle is used to inject the coal-air mixture into the furnace. The furnace is fired with propane overnight to maintain the required thermal conditions. Propane or coal fired as needed for testing. Additive gases, such as H_2S or SO_2 may be added to the propane at the burner. These gases may also be added to the combustion air or to the coal primary air if required.

The sorbent may be added to the system in several ways: pulverized with the coal, added with the coal in the primary air, added with the staging air (either at the burner face or downstream) or added directly into the furnace with a small amount of transport gas (either air or nitrogen). The sorbent is fed with a small, twin-screw volumetric feeder. The sorbent is transported from the feeder to the injection location with metered gas (either air or N_2).

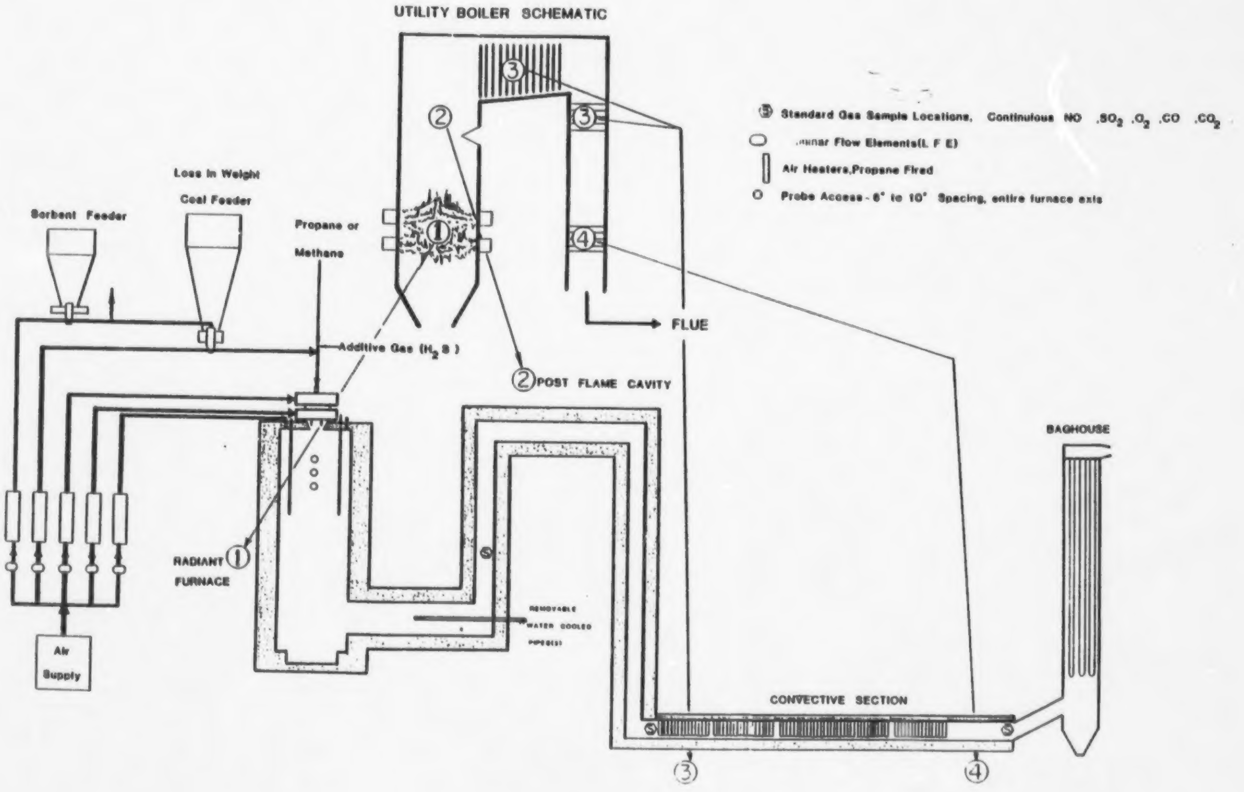

UTILITY BOILER SCHEMATIC
③ Standard Gas Sample Locations, Continuous NO ,SO2 ,O2 ,CO ,CO2
Laminar Flow Elements(L F E)
Air Heaters,Propane Fired
Probe Access - 6" to 10" Spacing, entire furnace exis
Loss in Weight Coal Feeder
Sorbent Feeder
Propane or Methane
Additive Gas (H2 S)
①
②
③
④
FLUE
② POST FLAME CAVITY
RADIANT ① FURNACE
REMOVABLE WATER COOLED PIPE(S)
Air Supply
CONVECTIVE SECTION
BAGHOUSE
③
④

Figure B-7. Functional schematic of boiler simulator furnace.

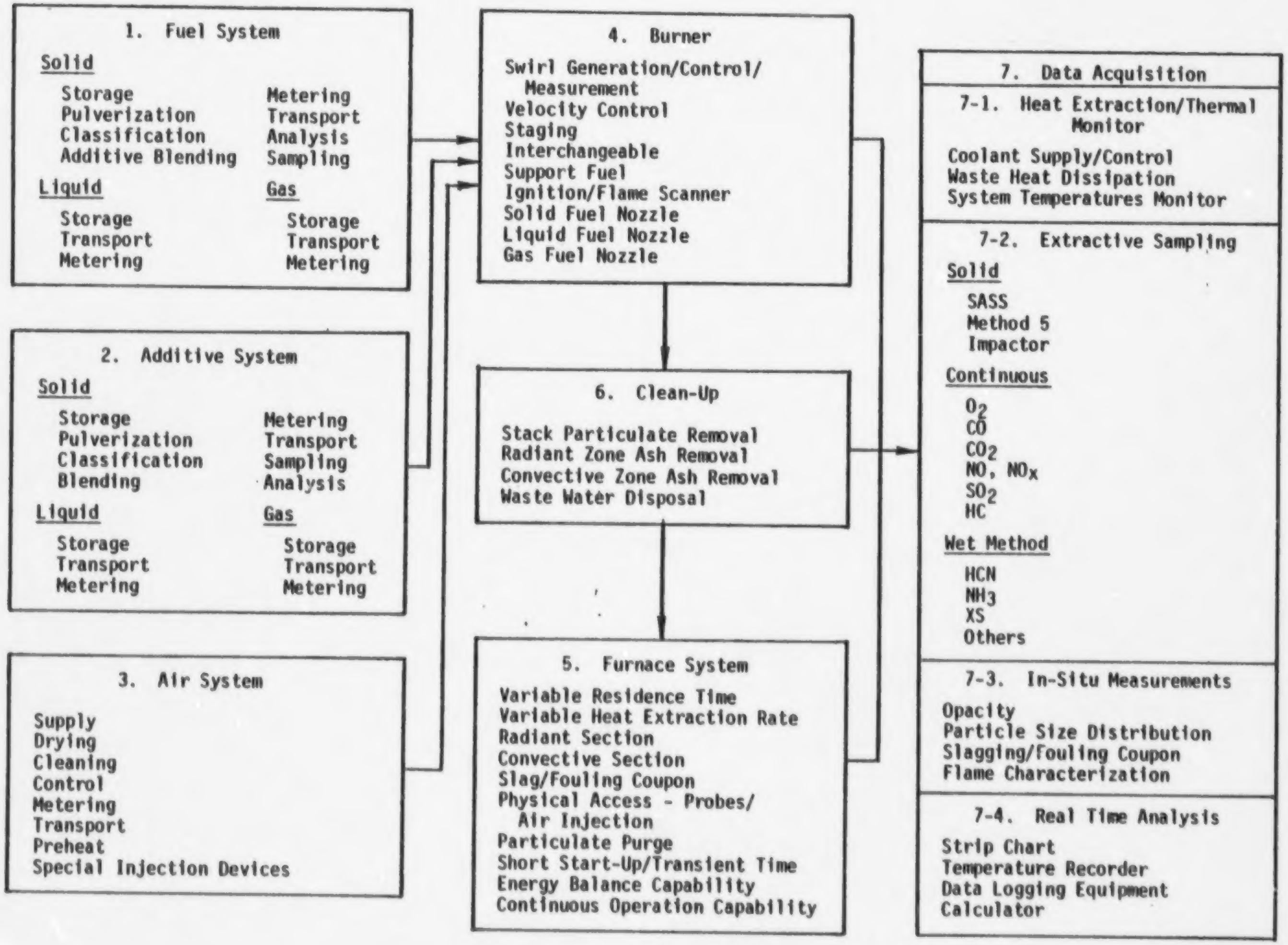

1. Fuel System
Solid
Storage
Pulverization
Classification
Additive Blending
Metering
Transport
Analysis
Sampling
Liquid
Storage
Transport
Metering
Gas
Storage
Transport
Metering
2. Additive System
Solid
Storage
Pulverization
Classification
Blending
Metering
Transport
Sampling
Analysis
Liquid
Storage
Transport
Metering
Gas
Storage
Transport
Metering
3. Air System
Supply
Drying
Cleaning
Control
Metering
Transport
Preheat
Special Injection Devices
4. Burner
Swirl Generation/Control/Measurement
Velocity Control
Staging
Interchangeable
Support Fuel
Ignition/Flame Scanner
Solid Fuel Nozzle
Liquid Fuel Nozzle
Gas Fuel Nozzle
6. Clean-Up
Stack Particulate Removal
Radiant Zone Ash Removal
Convective Zone Ash Removal
Waste Water Disposal
5. Furnace System
Variable Residence Time
Variable Heat Extraction Rate
Radiant Section
Convective Section
Slag/Fouling Coupon
Physical Access - Probes/Air Injection
Particulate Purge
Short Start-Up/Transient Time
Energy Balance Capability
Continuous Operation Capability
7. Data Acquisition
7-1. Heat Extraction/Thermal Monitor
Coolant Supply/Control
Waste Heat Dissipation
System Temperatures Monitor
7-2. Extractive Sampling
Solid
SASS
Method 5
Impactor
Continuous
O_2
CO
CO_2
NO, NO_x
SO_2
HC
Wet Method
HCN
NH_3
XS
Others
7-3. In-Situ Measurements
Opacity
Particle Size Distribution
Slagging/Fouling Coupon
Flame Characterization
7-4. Real Time Analysis
Strip Chart
Temperature Recorder
Data Logging Equipment
Calculator

Figure B-8. Summary of design criteria for Boiler Simulator Furnace.

Pressures at the feeder exit are regulated to prevent plugging of the delivery tube or aspiration of sorbent from the feeder. The coal and sorbent supply systems are shown schematically in Figure B-9.

The combustion air is supplied by a dedicated 300 scfm, 100 psig capacity compressor. The air is cooled, dried, regulated to ∿45 psig and supplied to a 5 stream manifold. Each air stream is metered and controlled separately. Flow rates are indicated by pressure drops across laminar flow elements (read manually with inclined manometers and, for computerized on-line data acquisition, with pressure transducers). Each metered air stream flows through a propane fired recuperative air heater. The five air streams are used for: variable-swirl, secondary air (axial and swirl air streams); primary (coal transport) air; tertiary or staging air; and sorbent transport.

The furnace is equipped with a versatile distributed mixing burner modeled after the EPA prototype burner. The burner is shown schematically in Figure B-11. Two secondary air streams are supplied to the burner. The secondary air swirl can be controlled by modifying the swirl and axial air flow rates. The burner has four external staging air ports supplied with separately metered tertiary air. The tertiary air injection velocity is modified by changing the air injector size. The burner is designed to fire coal or propane. Three fuel injectors are available: two coal injectors to supply the fuel in an axial core or radially spread by a divergent in the nozzle, and an axial propane injector.

The furnace is designed to simulate the time/temperature and velocity characteristics of coal-fired boilers and consists of the following components:

- Radiant Combustion Zone
- Postflame Cavity
- Convective Heat Exchange Sections--Primary, Secondary, and Reheat Superheaters
- Economizers and Air Heaters

The design specifications of these components are summarized in Table B-1.

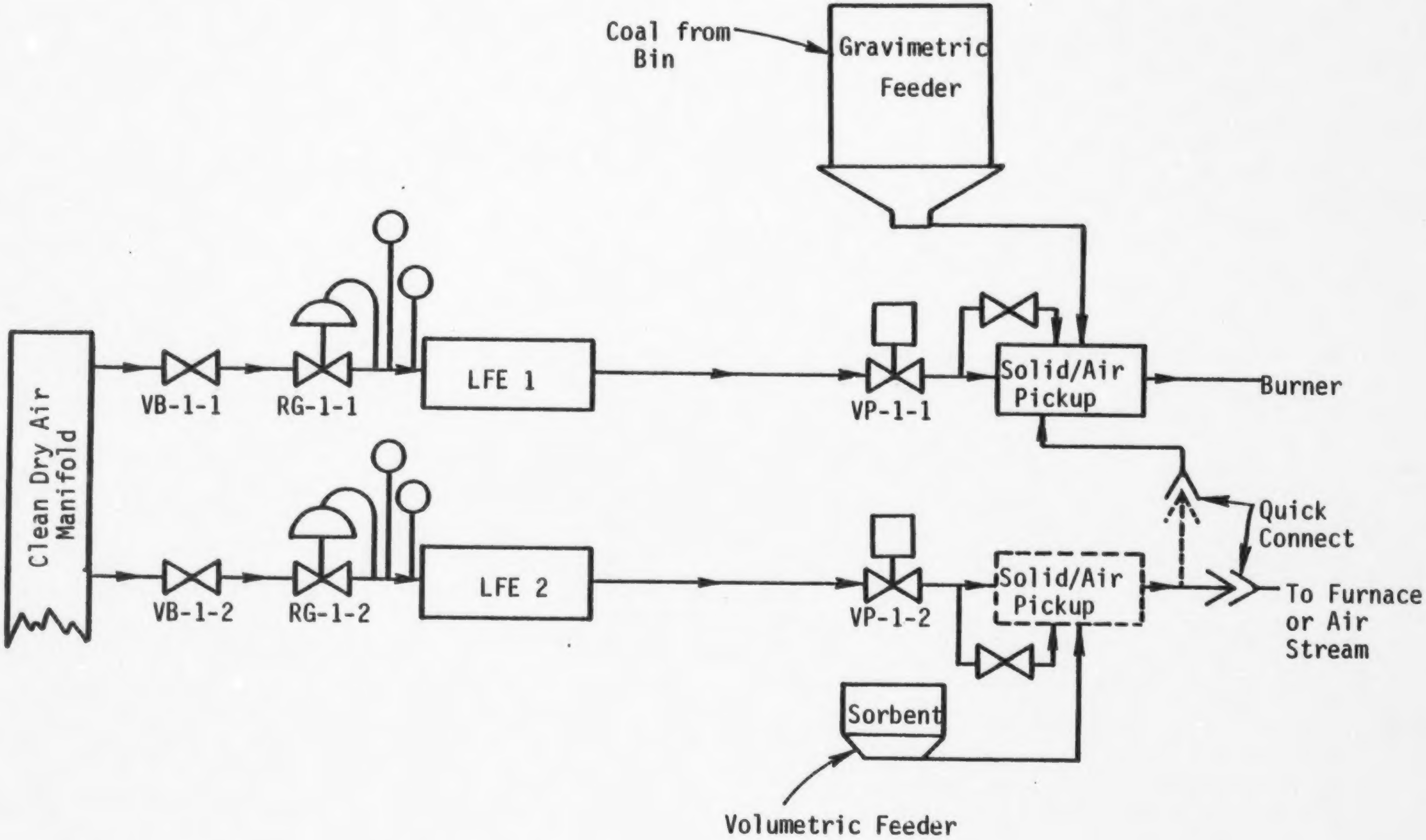

Coal from Bin
Gravimetric Feeder
Clean Dry Air Manifold
VB-1-1
RG-1-1
LFE 1
VP-1-1
Solid/Air Pickup
Burner
VB-1-2
RG-1-2
LFE 2
VP-1-2
Solid/Air Pickup
Quick Connect
To Furnace or Air Stream
Sorbent
Volumetric Feeder

Figure B-9. Schematic of coal and sorbent feed systems.

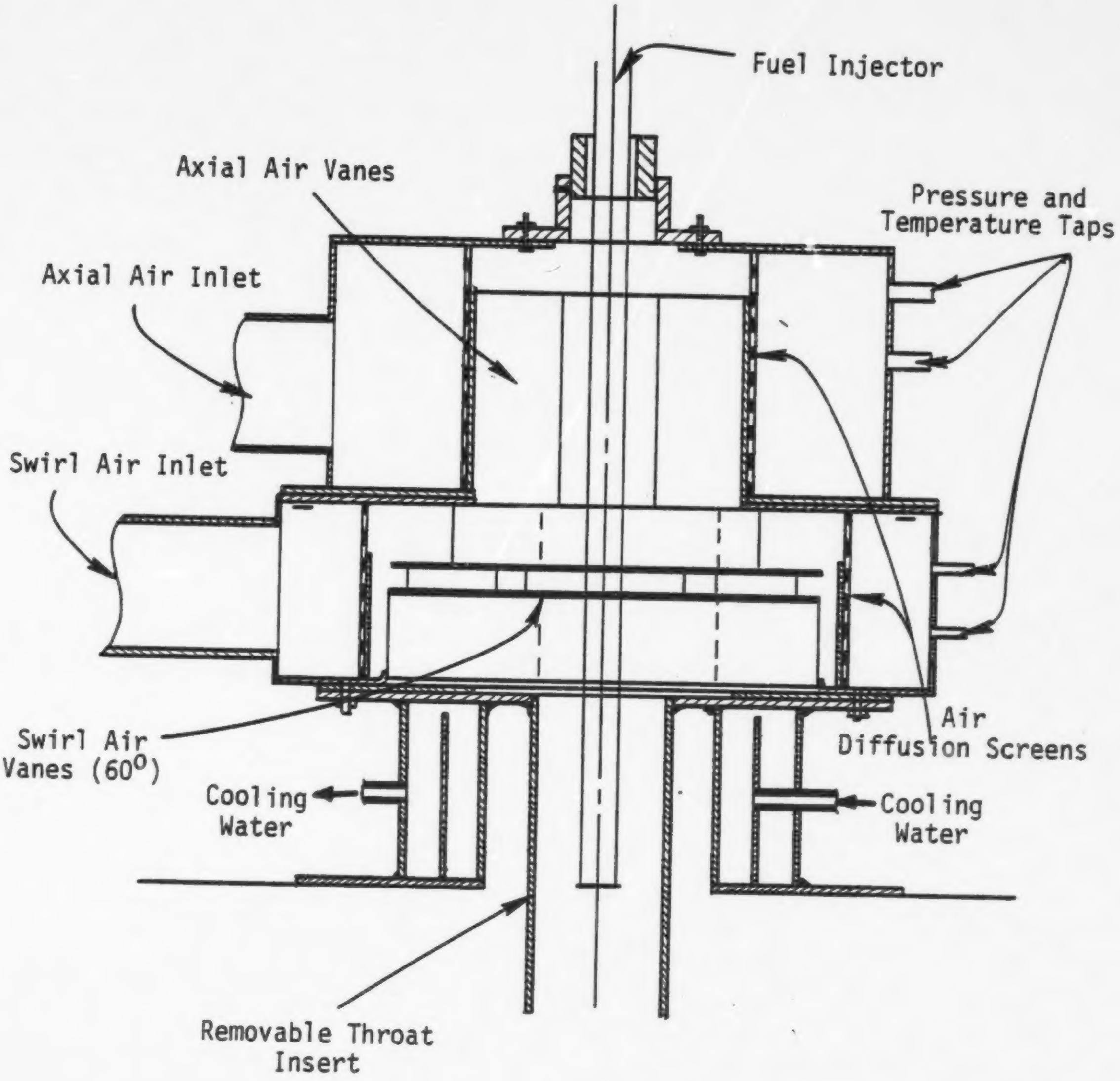

Fuel Injector
Axial Air Vanes
Pressure and Temperature Taps
Axial Air Inlet
Swirl Air Inlet
Swirl Air Vanes (60°)
Air Diffusion Screens
Cooling Water
Cooling Water
Removable Throat Insert

Figure B-11. Distributed mixing burner schematic, BSF (tertiary air ports not shown).

TABLE B-1. BOILER SIMULATOR FURNACE COMPONENT DESIGN SPECIFICATIONS

I. Radiant Section Design Specifications - General

Internal Dimensions	24" ID x 93" Long
External Dimensions	36" OD x 96" Long
Orientation	Horizontal
Maximum Designed Gas Temperature	3200 F
Furnace Volume	24.35 ft^3
Internal Surface Area	54.98 ft^2
Number of Modules	Four: One (1) Burner Module Two (2) Regular Modules One (1) Exhaust Module
Wall Construction	Adiabatic Modules and Exhaust Module Consisting of 4 Wall Layers (inside to outside): 2½" B & W Mix 48C (or similar) 2" 3000 F Insulation Cylinder 1½" Castablock Insulation 1/8" Carbon Steel Casing High Quench Modules Consisting of 2 Wall Layers: 3" B & W Mix 48C (or similar) 1/8" Carbon Steel Casing
Residence Time @ 1 x 10^6 Btu/hr SR_T = 1.2 T_{mean} = 2800 F	1.2 seconds
Total Port Area/%	177 in^2/2.24%

TABLE B-1. BOILER SIMULATOR FURNACE COMPONENT DESIGN SPECIFICATIONS (CONT.)

III. Superheater/Reheater Design Specifications - Active Heat Transfer Tube Bundles

	Superheater	Reheater
Tube Arrangement	Cross Flow Banks	Cross Flow Banks
Tubing Size	3/8"	3/8"
Wall Thickness	0.035"	0.035"
Tubing Spacing Perpendicular to Flow	2.0"	2.0"
- Parallel to Flow	0.85"	0.85"
Number of Rows	148	148
Tube Length per Row	31"	27"
Total Length	382 ft	333 ft
Total Exchange Surace Area	37.5 ft^2	32.7 ft^2
Estimated Heat Transfer Coefficient	7.1 Btu/hr-ft^2-^oF	7.1 Btu/hr-ft^2-^oF
Esimated Heat Extraction Rate	472,000 Btu/hr	250,400 Btu/hr
Cross-Section Area of Tube	11.6 in^2	10.1 in^2
Free Flow Area (gas side)	52.4 in^2	38.9 in^2
% Tube Area	18.2%	20.6%
Gas Velocity	41 ft/sec	39 ft/sec
Estimated Residence Time	0.34 sec	0.37 sec

TABLE B-1. BOILER SIMULATOR FURNACE COMPONENT DESIGN SPECIFICATIONS (CONT.)

IV. Air Heater Design Specifications - Active Heat Transfer Tube Bundles

Tube Arrangement	Cross Flow Banks
Tube Size	3/8"
Wall Thickness	0.035"
Tube Spacing Perpendicular to Flow	2.0"
- Parallel to Flow	0.85"
Number of Rows	148
Length per Row	23"
Total Tube Length	284
Total Tube Surface Area	27.8 ft^2
Estimated Heat Extractions Rate	7.1 Btu/hr-ft^2-^{o}F
Estimated Heat Extractions Rate	109,000 Btu/hr
Cross-Section Area of Tube	8.6 in^2
Free Flow Area	27.4 in^2
% Tube Area	23.9%
Gas Velocity	34 ft/sec
Estimated Residence Time	0.58 second

TABLE B-1. BOILER SIMULATOR FURNACE COMPONENT DESIGN SPECIFICATIONS (CONT.)

IV. Air Heater Design Specifications - General

Internal Dimensions	8" x 6" Section x 14'0"
External Dimensions	14" x 14" Section x 14'0"
Total Volume	4.67 ft^3
Internal Surface Area	32.7 ft^2
External Surface Area	65.3 ft^2
Orientation	Horizontal
Design Gas Temperature	850 F - 250 F
Wall Construction	3" Thick Castablock
Module	2 - Adaptor = 1' long 2 - Regular = 6' long
Nominal Conduction Heat Transfer Coefficient	0.50 Btu/hr-ft^2-^oF
Estimated Heat Loss	235 Btu/hr-ft^2
Estimated Total Conduction Heat Loss	7,700 Btu/hr
Estimated Residence Time	0.58 second
Estimated Weight	800 lb

The cylindrical radiant combustion section is designed to simulate the region near the circular burners of a boiler where the flow is axisymmetric. The radiant section is made of four cylindrical modules three feet in diameter and two feet long. A typical module is shown schematically in Figure B-12.

The postflame cavity was required to:

- Provide a reaction volume similar to the space above the burner zone in a boiler.
- Create a region where the bulk gas velocity is similar to that of the gases leaving the active burner zone, hence simulating bottom ash deposition.

The dimensions of the postflame cavity and the relative orientation of the radiant furnace and postflame cavity portions of the BSF was changed during the bench scale testing. The original postflame cavity was an insulation board lined duct 9' x 9' x 32' (as in Table B-1). The current(and final) postflame cavity is refractory lined, has a cross-section which decreases stepwise from 12' x 18' at the entrance to 9' x 9' at the exit and is about 18 ft long. The new transition from the radiant to the postflame section were constructed.

A horizontal duct 14 feet long of inlet cross-section 8" x 8" and with active convective heat transfer tubes simulates the primary superheaters. The reheat superheater is similar in design, but has an 8" x 7" internal flow section. The economizer and air heater sections differ from the superheaters in their operating temperatures and construction as indicated in Table B-1. The heat transfer tubes are air cooled and arranged at 90^{o} to the direction of gas flow. Varying the coolant flow rates controls the rate of heat removal in each convective section. All of the convective sections are insulated to minimize uncontrolled heat losses. A schematic of a convective section is shown in Figure B-13.

A key design feature of the BSF is the ability to "tailor" the thermal history of the sorbent and combustion products. The temperature profile in the convective sections is controlled by controlling the coolant flow rates (as discussed above). Upstream, the furnace is designed to minimize heat

Dimensions: Inches

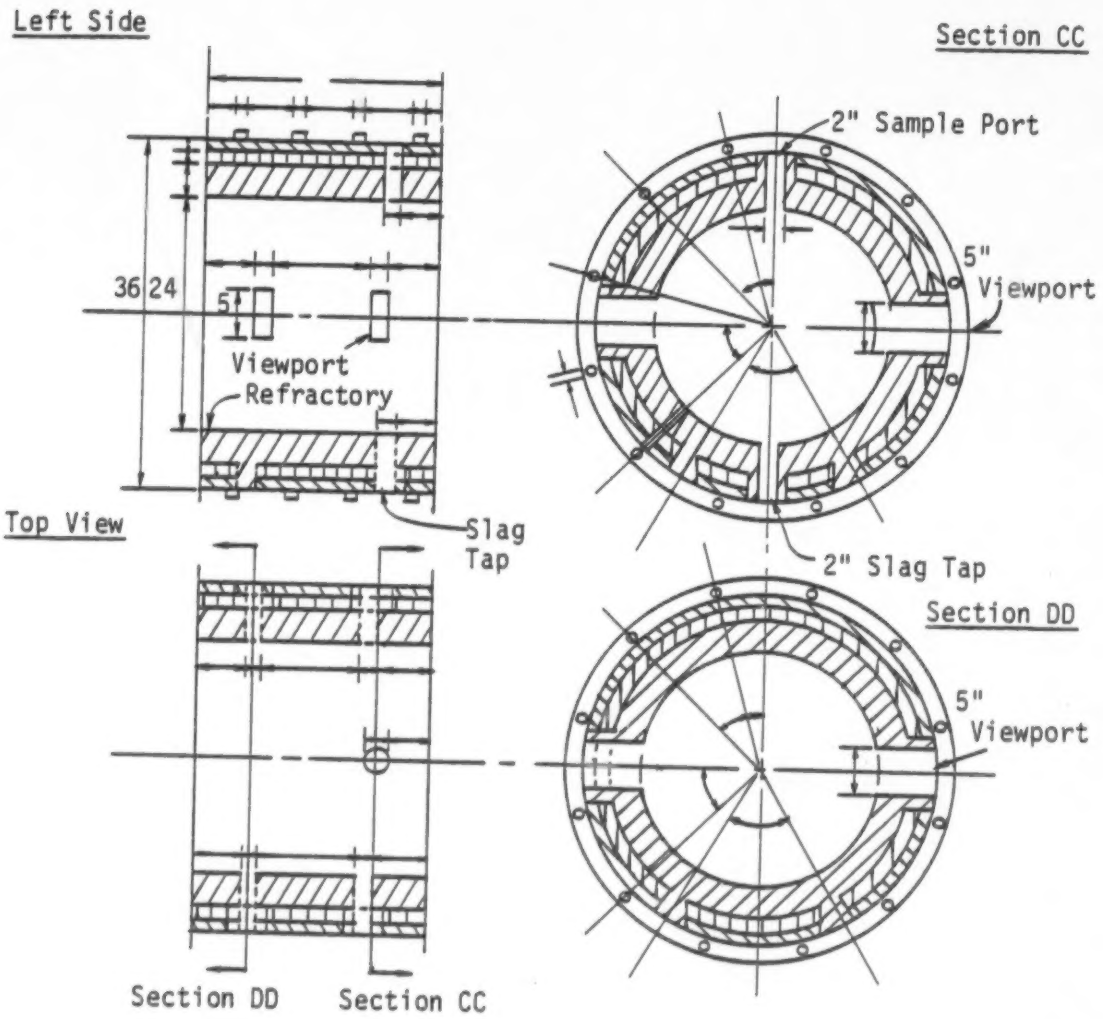

Left Side
Section CC
2" Sample Port
5" Viewport
36
24
5
Viewport
Refractory
Slag Tap
2" Slag Tap
Top View
Section DD
5" Viewport
Section DD
Section CC

Figure B-12. BSF - radiant adiabatic furnace module - concept.

Dimensions: Inches

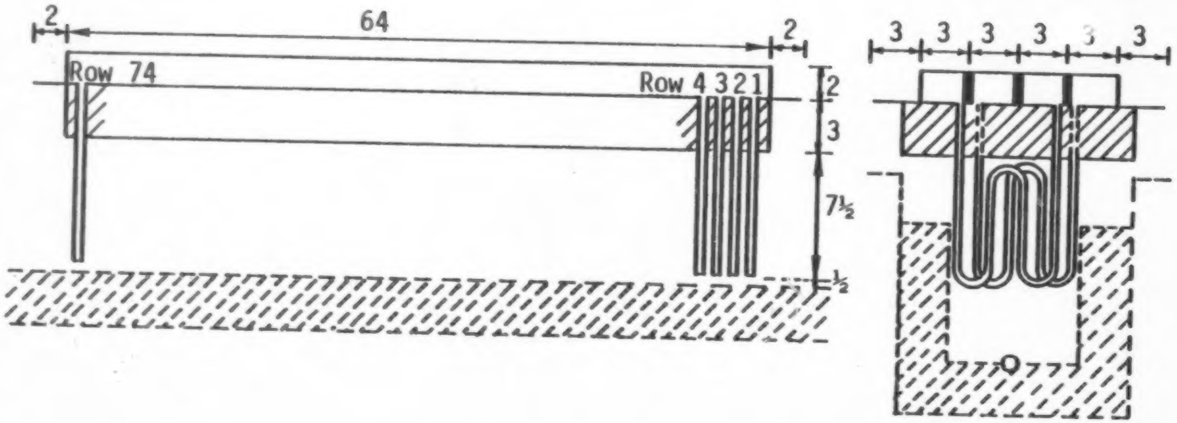

2
64
2
Row 74
Row 4 3 2 1
2
3
7½
½
3
3
3
3
3
3

Figure B-13. BSF - convective air cooled superheater model.

losses to the atmosphere. The thermal history in the radiant and postflame cavities is modified with removable cooling coils (in the radiant furnace) and pipes (in the radiant-post flame transition). Various heat extraction levels are possible using these coils and rods.

A typical bituminous coal will produce about 8 lb/hr of ash when fired at the BSF nominal load of 1.0 MBtu/hr. The ash loading will increase with sorbent injection or increased coal ash loading. Deposition of slag and ash on the radiant and post flame walls cannot be avoided. (The handling of these deposits will be discussed in Section B.3).

Fly ash which passes through the furnace is collected from the exhaust in a baghouse. The baghouse is equipped with special fabric bags which will allow high temperature (to ∿450 F) operation when needed. The baghouse is exhausted with an induced draft fan and the clean exhaust gas is discharged. The ID fan is equipped with a damper and the furnace/convective sections are generally run at ambient or slightly (up to 6" H_2O at the burner) positive pressure to prevent dilution by in-leakgage of air.

The BSF system is very complex; numerous variables such as:

- Input parameters including fuel and air flow rates and temperatures, coolant temperatures and rates;
- Output parameters including gas product concentrations and temperatures;
- System operational parameters including furnace temperatures, pressures and ancillary equipment (i.e., compressor, fans, cooling tower) operation;
- Computed "performance" parameters such as mass and energy balances, pollutant formation rates, and bulk gas velocities and residence times.

are monitored on a continuous basis. A computerized on-line data acquisition system is used to help monitor and record system operating parameters. All of the experimental and data acquisition procedures may proceed without the computer. (Sample gas compositions, fuel and air flow rates, furnace temperatures and pressures, etc. can all be read and recorded manually if necessary).

B.3 Boiler Simulator Furnace Operating Experience

The original configuration of the Boiler Simulator Furnace is shown in Figure B-14. The cylindrical radiant furnace was horizontal and equipped with a slag trough and taps along the "bottom" of the cylinder. The post flame cavity (PFC) was designed to simulate the average bulk gas velocity and residence in the main firebox region of a boiler. The PFC was 9" x 9" in internal cross section and 32 ft long. The steel shell was lined with 3" of a high insulating fiberboard. The transition from the radiant to post flame section was simply a rectangular hole in the top of the "exhaust" cylindrical section of the radiant furnace. At this exhaust section the flow changed direction (90^0), the cross sectional area changed from ~ 3 ft^2 to 0.6 ft^2, and the bulk gas velocity went from ~ 6 ft/sec to ~ 32 ft/sec. The furnace plugged badly at this transition section. The need for injection of staging air at the base of the post flame cavity and the plugging problem instigated construction of a new radiant furnace exhaust section and PFC first leg. Figure B-15 shows a schematic of the BSF with these new sections in place.

The insulation board in the post flame section was very fragile. Ash deposits on the board caused it to deteriorate. When deposits were scraped from the walls (necessary because eventually the passages closed up with ash deposits) the board came off with the ash. The post flame section was redesigned and rebuilt because of these problems. The new PFC was shorter than the original, was lined with dense castable refractory and the flow area was reduced from 3.0 ft^2 to 0.6 ft^2 stepwise rather than abruptly at the transition to the PFC. Figure B-16 shows the cross-sectional area of the BSF as a function of axial distance from the burner for the two post flame sections.

The radiant section of the Boiler Simulator Furnace was originally a horizontal cylinder. The configuration was chosen to simulate ash dropout in the near burner region of a wall fired burner. The horizontal, radiant cylinder slagged during all of the high-temperature, coal fired runs and gradually filled with slag. The slag taps did not work because when the tap was opened molten slag flowed into the hole, touched the cold refractory at the sides of the hole and solidified. The horizontal configuration puts some severe restrictions on minimum allowable fuel and air injection velocities (fuel and air injection velocities which are too low will cause the flame to sag, and

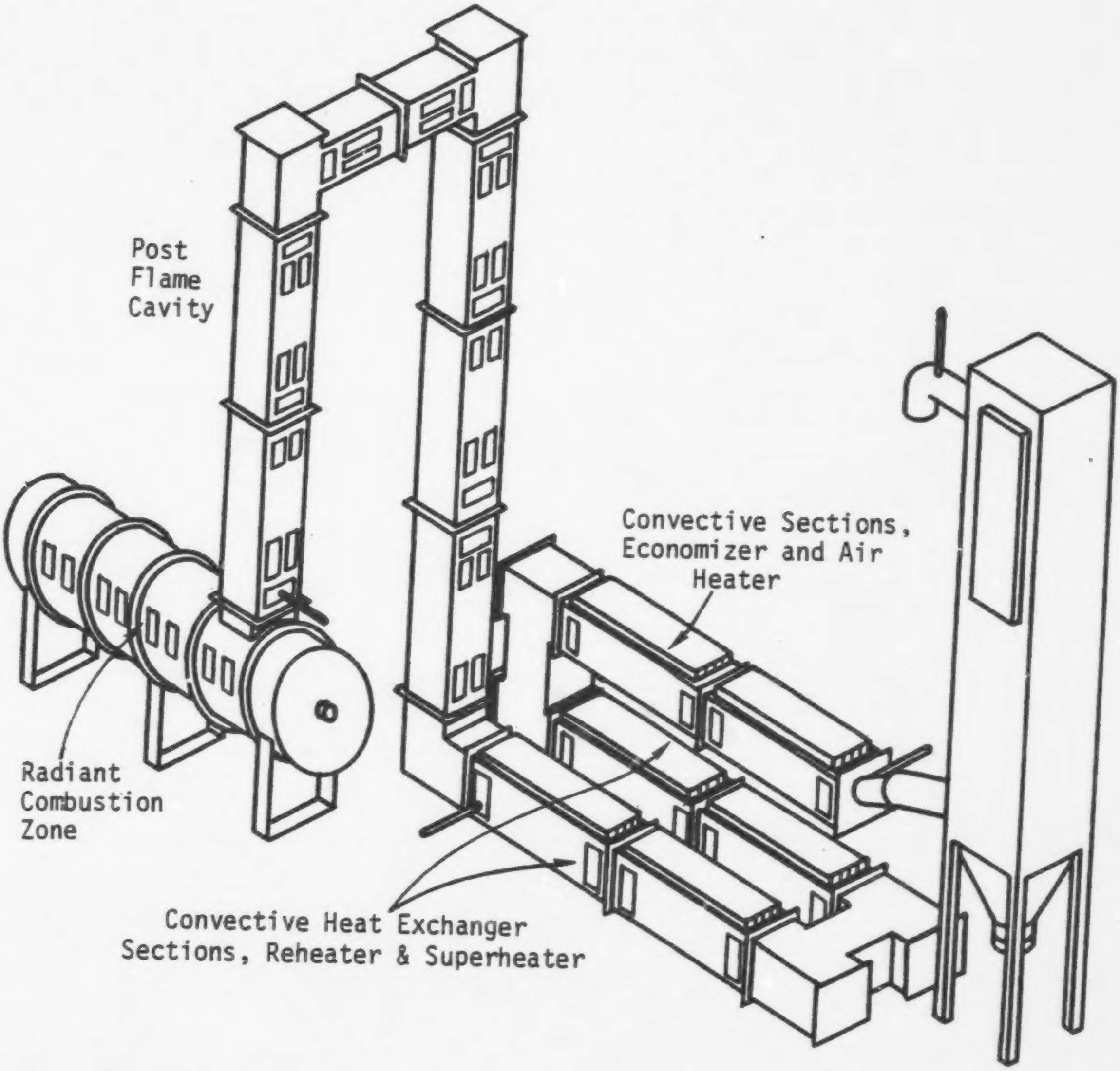

Post Flame Cavity
Convective Sections, Economizer and Air Heater
Radiant Combustion Zone
Convective Heat Exchanger Sections, Reheater & Superheater

Figure B-14. Boiler Simulator Furnace - original configuration.

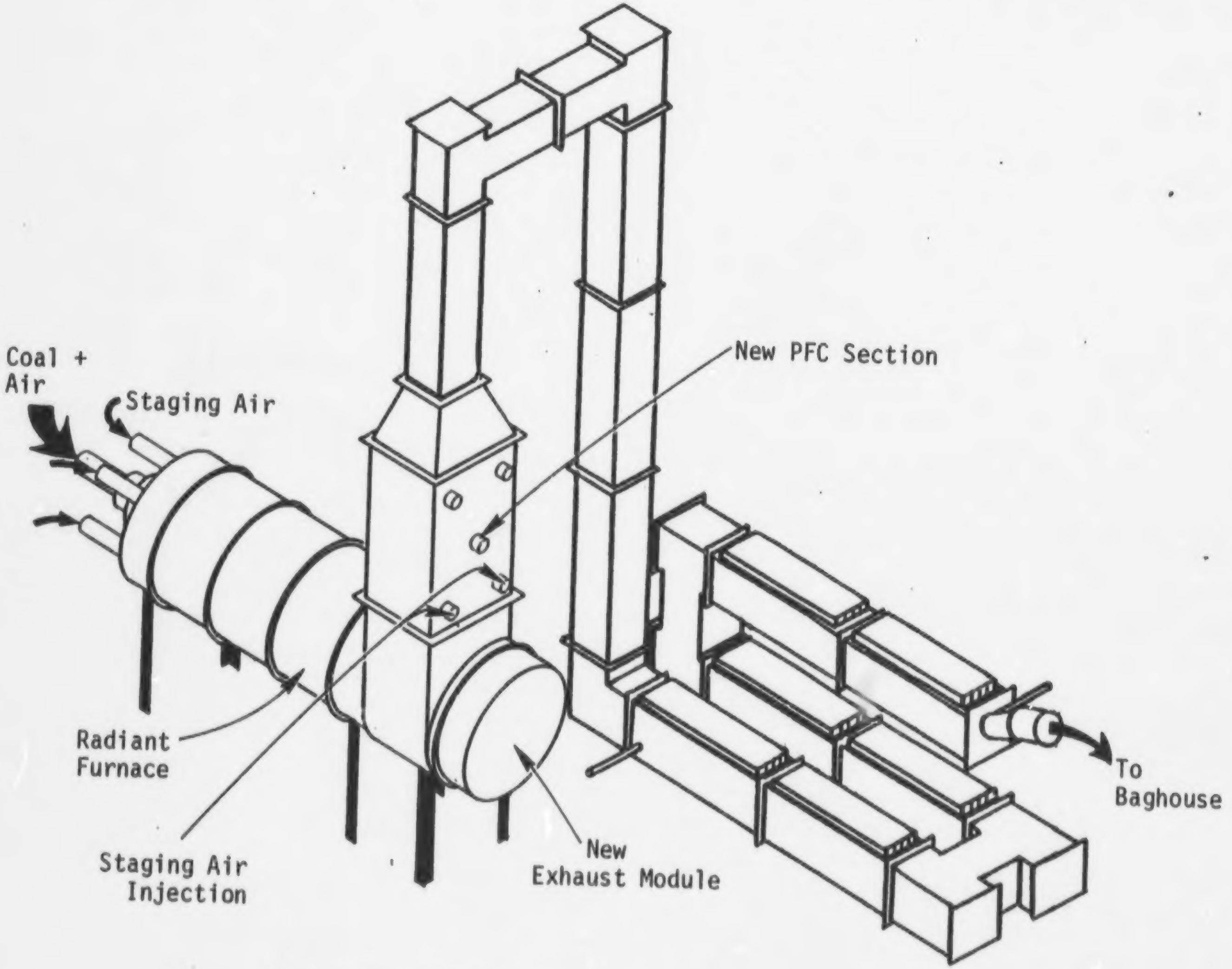

Coal +
Air
Staging Air
New PFC Section
Radiant
Furnace
Staging Air
Injection
New
Exhaust Module
To
Baghouse

Figure B-15. Boiler Simulator Furnace schematic.

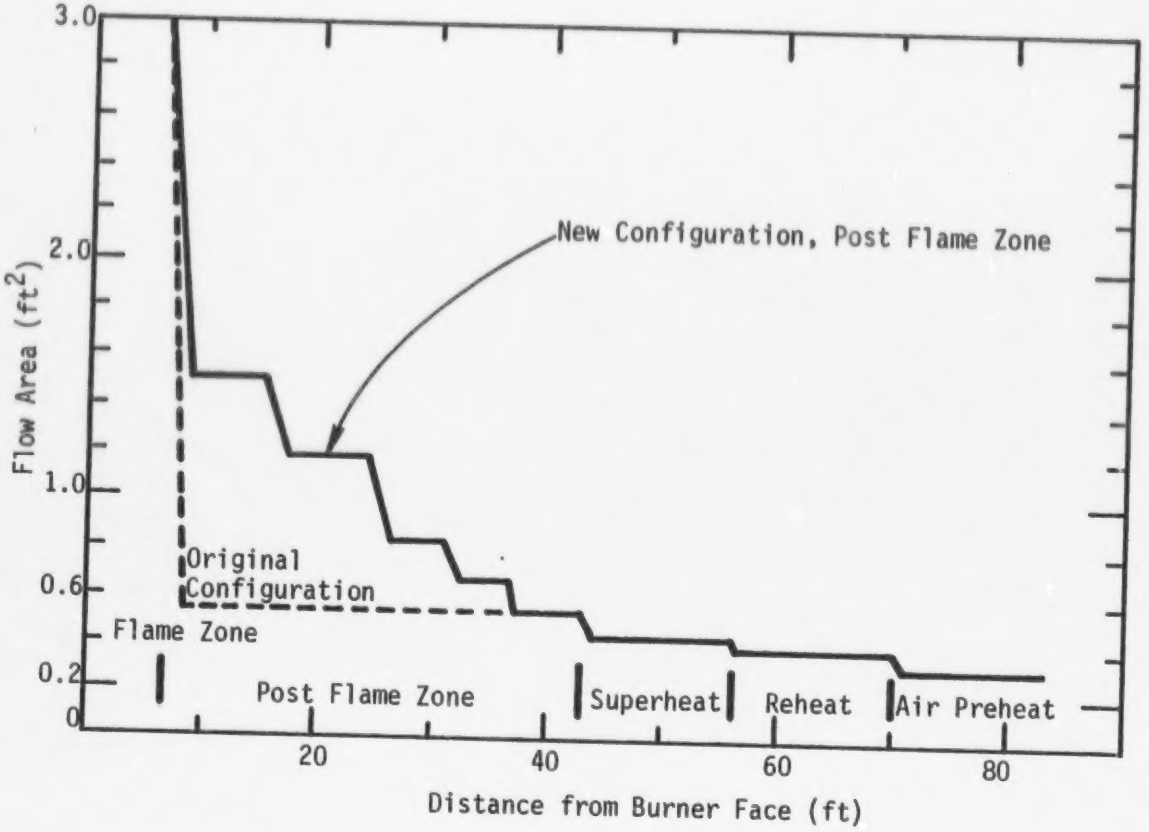


Figure B-16. BSF cross-sectional flow area versus axial distance.

if even lower, may cause ignition and stability problems). The furnace configuration was changed to reduce minimum velocity restructions and to ease ash handling problems. The radiant furnace was tipped up and the new (refractory walled) post flame section was installed. A schematic of the resulting down-fired furnace is shown in Figure B-17. Ash handling procedures were simplified, the post flame section was scraped on a regular basis and the slag pot at the bottom of the radiant furnace was changed out when needed. (The slag which had accumulated in the horizontal radiant furnace melted and ran into the slag pot the first time the furnace was heated in the vertical configuration).

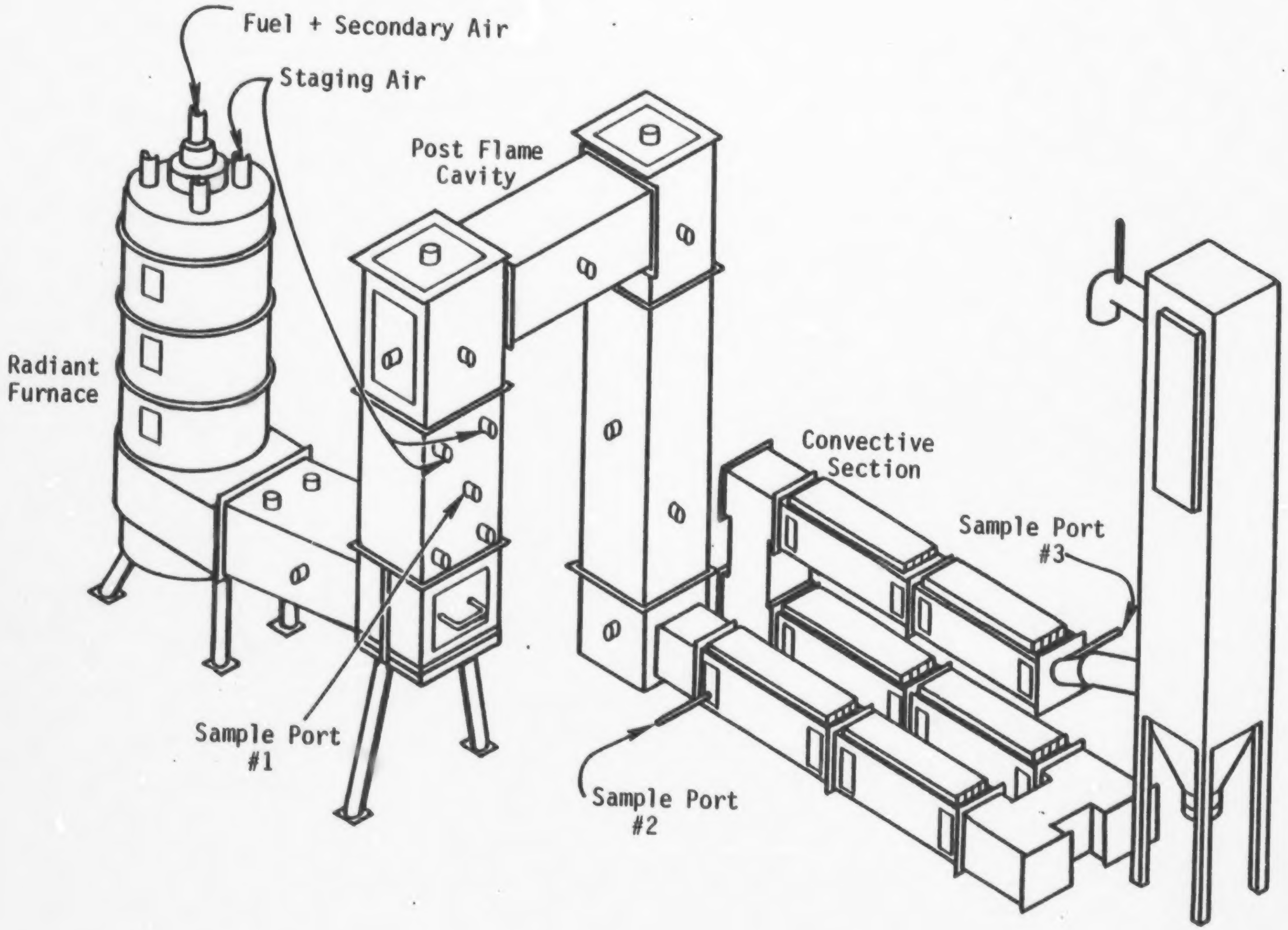

Fuel + Secondary Air
Staging Air
Post Flame Cavity
Radiant Furnace
Convective Section
Sample Port #3
Sample Port #1
Sample Port #2

Figure B-17. Downfired Boiler Simulator Furnace.

APPENDIX C

CONVERSION TABLE
FROM ENGLISH TO
METRIC UNITS

TABLE C-1 CONVERSION TABLE FROM ENGLISH TO METRIC UNITS

1 lb/hr = 0.4536 Kg/hr
1 ton/hr = 907.2 Kg/hr
1 Btu/hr = 0.29307 Watts
1 Ft^2 = 0.0929 M^2
1 Btu/lb = 2.326 KJ/Kg
1 in. = 2.54 cm
1 in/Hg = 3386.5 N/m^2
1 Ft^3 = 0.0284 M^3
1 Ft = 0.3048 M
1 Ft/Sec = 0.3048 M/Sec
1 in^2 = 6.45 cm^2
1 Btu/hr Ft^2 ^{o}F = 5.6782 W/M^2 ^{o}C
^{o}F = $1.8^{o}C + 32$